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BURNER TILE TESTING FOR DEACTIVATION FURNACE AFTERBURNER (AFB).(U)
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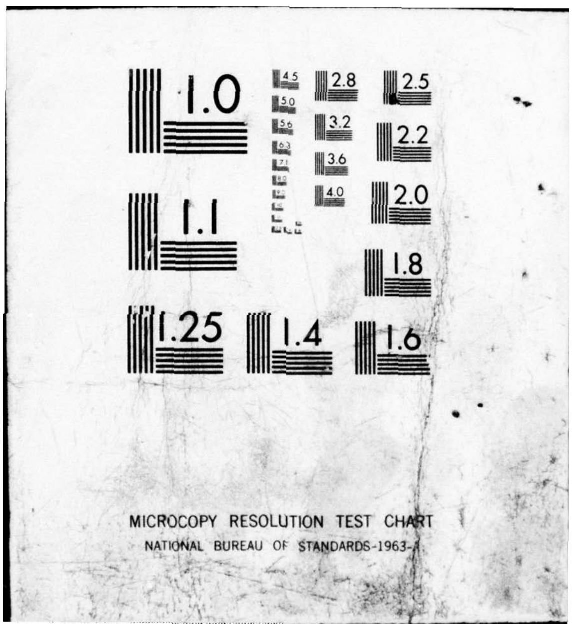
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This report contains the description, results and conclusions of tests to measure reached within the redesigned Deactivation Furnace Afterburner burner tiles, and to analyze the effects of temperature on future life expectancy of these tiles.

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6 BURNER TILE TESTING
for
DEACTIVATION FURNACE AFTERBURNER (AFB).

CHEMICAL AGENT MUNITIONS DISPOSAL SYSTEM(CAMDS)
TOOELE ARMY DEPOT
Tooele, Utah

9 Final rept.,

12 60p.

Prepared by:

10 J. D./McGannon

MIDLAND-ROSS CORPORATION
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TABLE OF CONTENTS

1. INTRODUCTION

Premature tile (block) failures for the vaporizing oil burners have heretofore been attributed to numerous causes. Burner design deficiencies existed for the afterburner application, requiring a program including re-design, test and reporting phases. Final design modifications included a circular tile cross-section, propane pilot ignition, and alloy wire reinforced refractory. The goal of this program was to measure temperatures reached within the redesigned Deactivation Furnace Afterburner (AFB) burner tiles, and to analyze the effects of temperature on future life expectancy of these tiles.

Burner tile temperatures were monitored during specified ignition, heating, normal operation, cooling, and power failure conditions. Monitoring was accomplished by recording temperatures of type R thermocouples cemented into pre-cast holes of the "B Burner" tile. Several redundant couples were applied to this burner tile such that the "A Burner" would not be weakened by thermocouple holes. This provides one "virgin" tile for long term evaluation without the doubt caused by potentially destructive testing techniques.

The report will show that the theoretical refractory tensile strength, in terms of modulus of rupture (MOR), is exceeded by the results in several cases. The excess stress is shown to be much lower, however, for the fiber reinforced refractory. Possible reinforced refractory failure is predicted in smaller areas than for the conventional refractory matrix. Further, complete radial crack failure likely will not

occur due to the strength and crack propagation resistance of the fiber reinforced refractory. These predictions are based upon theoretical calculations for a cylindrical thermal stress model.

Several recommendations are included in the report. Higher thermal conductivity refractory materials and added external insulation modifications are presented to reduce temperature gradients and resultant stresses. Lower concentration alumina refractories suggest reduced stress with lower thermal expansion factors. A new "hooked" wire reinforcement material is also discussed briefly as an advantageous modification.

It is probable that a satisfactory solution for extending tile life has been achieved with the current design. A maximum temperature of $2250^{\circ}F$ was recorded for the tile inner diameter during the tests. This is well below the $3400^{\circ}F$ maximum service temperature of the refractory matrix. The $2250^{\circ}F$ temperature only moderately exceeds the oxidation limit for the 330 alloy reinforcement wire. Any failure should be more closely related to tile temperature gradients and resultant thermal stress. The crack propagation resistance of the fiber reinforced material should prevent extension of any local stress cracking. Therefore, it is recommended that the design be evaluated over an extended period of operation time to confirm the anticipated improvements discussed in this report.

2. SUMMARY

Some of the important information in this report is summarized in the following paragraphs.

2.1 Calculated stress levels for the outer 1/2" of the tile material exceeds allowable strengths in terms of MOR for normal operating temperatures. Stress appears to exceed 2000 psi when ultimate strength is about 1600 psi.

2.2 Normal operation results in compression stress at the tile I.D. However, rapid cooling during purge of a hot tile results in a thin layer of rather severe tension at the I.D. Theoretical strength is exceeded and local tensile cracking can be expected. Thermal cycling and ratcheting of the inner surface can extend minor cracks.

2.3 Slow heating of the tile should extend life. Instantaneous high fire ignition of a cold tile could develop a $2700^{o}F$ radial ΔT, with 4500 psi external tension and 7700 psi internal compression stresses resulting. The allowable tension and compression stresses would be greatly exceeded in this case.

2.4 Maximum flame temperatures of approximately $2800^{o}F$ can be expected, though recorded tile temperatures were somewhat lower. Refractories with at least $3000^{o}F$ service temperature should thus be applied for tile materials.

2.5 Existing burner capacity can be expected to yield approximately $900^{o}F$ temperature rise for the rated 3000 scfm effluent flow. The flow of 4150 scfm measured during tests would reflect approximately

750°F temperature rise.

2.6 Slow cooling of the afterburner is recommended to minimize or eliminate any additional cyclic thermal stress. The most recent SOP for cooling should thus be followed.

2.7 Potentially improved fibers could be applied to future designs. Hooked fibers of 330 alloy could offer improvements as could an increase in weight percentage of conventional fibers.

2.8 Lower percentage alumina refractories should be considered for future applications. Compatible service temperatures should be attainable with, say, a 50% alumina matrix. The lower alumina concentration materials have reduced thermal expansion coefficients. The lower coefficient reduces stresses developed for a given temperature gradient. Increased external tile insulation would also tend to reduce stresses, since temperature gradients would be reduced with lower radial heat fluid.

2.9 Though some local refractory failure (cracking) can be expected, substantially improved tile life is expected with the fiber reinforced material. The strength and crack propagation resistance of the core, i.e., sub-surface material should improve tile life dramatically. Longer term evaluation of the current design is recommended to confirm the anticipated improvement in life.

3. DESCRIPTION

The deactivation furnace afterburner is equipped with two Trane model 7028 vaporizing type oil burners. Refractory tile failures precipitated considerable effort in the area of design and application of this burner. The purpose of this test program was to gather data on the final design and to discuss the information attained.

Several design modifications were applied as a result of the decision to continue with the use of this burner equipment. Knowledge from modifications to other Chemical Agent Munitions Disposal System furnace equipment was applied to the AFB. The following list summarizes the changes which preceded this evaluation:

3.1 Design Modifications

3.1.1 Refractory material

Wahl, Inc., Wire-N-Cast material was used to cast the burner tiles. This refractory matrix is a 94% tabular alumina material with a CA-25 cement bond. Metallic fibers of RA330 alloy at 3% by weight completed the mixture. Fiber reinforced refractories are generally more resistant to failure from the stresses encountered with thermal shock. The tiles were oven dried to over 1000°F on a programmed time-temperature cycle prior to installation.

3.1.2 Burner tile shape

The external shape of the tiles had been square in cross-section by the original design. The circular shape was designed to increase wall section thickness and achieve a

more uniform thermal gradient.

3.1.3 Expansion ring

A split ring extension was applied to the mounting flange to provide support while allowing for thermal expansion.

3.1.4 Ignition system

Direct spark ignition of the burner was replaced by an interrupted propane pilot. Part of the test program evaluates the use of the pilot as a burner block preheat.

3.2 Field Testing

The basic objective of the tests was to gather information on burner tile temperatures during normal operation. One of the burners was fitted with platinum - 13% platinum-rhodium thermocouples. The location of the thermocouples is shown in Figure 1. Couples were cemented in pre-cast holes with alumina sleeves providing electrical isolation. Thermocouples were connected to a Westronics multi-point recorder, calibrated for the type R couples. The other burner was not altered for testing.

Additional data was recorded to complement burner tile temperatures. The following list discusses the data recorded:

3.2.1 Data recorded

3.2.1.1 Burner block O.D. and I.D. temperatures by direct reading temperature recorder.

3.2.1.2 Other temperatures, i.e.,from the Control Room instrumentation; afterburner, retort, and effluent gas actuals. Also, combustion air temperature was

recorded at the AFB level.

3.2.1.3 Static and differential pressures for combustion air, fuel oil, pilot flows, and zone suction in the afterburner. In addition, data on the retort input was also recorded.

3.2.1.4 Control operator % stroke for the AFB and retort from the CON instrumentation.

3.2.1.5 The time of data recording.

3.2.1.6 Flow rates and gas temperatures via velocity surveys during normal maximum temperature operation.

3.2.2 Test procedures

The procedure for data recording during the various test phases follows:

3.2.2.1 Propane pilot ignition and preheat

Commencing at approximately 10:00 a.m. on 2/14/78, the propane pilots were ignited and allowed to operate for four hours. The four hour period replaced the scheduled two hour test as auxiliary equipment was under repair. Pressure and temperature data was recorded at the AFB level and AFB temperature and operator % open were recorded in the CON, at 15 minute intervals. Pilot data was recorded for the "B-Burner" only, i.e., the one containing block thermocouples.

3.2.2.2 Main burner oil ignition and one hour min. fire

Beginning at 2:00 p.m. on 2/14/78, the AFB main oil

burners were ignited on oil and pilots were interrupted. Fuel and air pressures, air temperature, suction, etc., were recorded at 10 minute intervals at the AFB. AFB zone temperature and operator % were recorded at 15 minute intervals in the CON.

3.2.2.3 Heat-up period

At 3:00 p.m. on 2/14/78, the 50^{o}F/hr heat-up schedule was begun. Initially, a 12 1/2^{o}F per 15 minute increase in setpoint was begun under automatic control. This procedure was changed since input would be a function of time for any given change in setpoint. To achieve more meaningful data, manual control was applied. Under this scheme, the CON operator would increase or hold the previous % operator stroke on a 15 minute basis. This resulted in a fixed input over the adjustment cycle, rather than one dependent on temperature deviation from setpoint. The net heating schedule was somewhat altered from the SOP, however, as a result of this procedure. This item is discussed in later sections of this report.

Data was recorded at 15 minute intervals at the AFB level for input parameters, suction, etc. The completion of AFB data gathering was communicated to the CON, where controller temperatures and

percentages would be recorded, followed by an input increase or hold condition at the operator's discretion. Data for the retort combustion system was also recorded by CAMDS personnel during this period. At the completion of heating, i.e., at normal operating temperatures, velocity surveys were conducted by CAMDS personnel to determine related volume flows otherwise unmeasurable. Surveys were conducted at the slots under the double tipping valve, the retort burner end infiltration valve, retort combustion air manifold, and the effluent gas pipe. These tests were conducted on 2/15/78.

3.2.2.4 Simulated power failure tests

Originally planned as a flame failure test, simulated power interruption was selected as a more severe condition. Under power failure, the entire system must be restarted rather than the afterburner only. Two tests were conducted, with data recording for one hour after re-ignition, i.e., at 15 minute intervals. Data was recorded for the "B-Burner" only, in similar fashion to the heat-up period. No reheat schedule was followed. The afterburner was allowed to recover temperature as rapidly as possible.

3.2.2.5 Cool-down period

Beginning at approximately 5:00p.m. on 2/15/78, the cool-down cycle was initiated. Data was recorded as in the heat-up period. Input adjustments were again manual at the operator's discretion. Confusion over old versus new SOP lead to a reduced time cooling cycle over that planned as discussed in subsequent report sections.

4. RESULTS

Raw data and calculations based upon raw data have been plotted in a series of curves attached to this report. The contents and associated figure numbers are presented in the following table:

Test Phase	Figure No.	Description
Pilot ignition	2	Burner block & AFB zone temp. vs time
Main burner ignition and 1 hour min. fire	3	Burner block & AFB zone temp. vs time
Heating cycle	4	Burner block temperatures vs time
	5	Afterburner, retort, and effluent temperatures vs time
	6	Control operator position vs time
	7	Excess air level and AFB input vs time
Power Interruption	8	Burner Block temp. vs time - Test #1
	9	Burner Block temp. vs time - Test #2
	10	AFB Temperature & control % vs time
Cooling Cycle	11	Burner Block temperature vs time
	12	Afterburner, retort, and effluent temperatures vs time
	13	AFB and retort controller positions vs time
	14	Excess air and AFB input vs time

Some of the calculated values and some further results are presented under the following Discussion section.

5. DISCUSSION

Burner tiles are subjected to severe conditions of high temperature and rapid rate of change of temperature. The Trane burner tile shape is particularly vulnerable to these conditions. First, the reduced exit port diameter results in higher internal temperatures than for conventional burners. This is a result of the inability to release heat by radiation through the nozzle end. Second, the results of even minor tile cracks can be destructive due to the positive combustion chamber pressure. Flame temperature gases can be forced through radial cracks, resulting in local insulation burnout around the burner and hot spots under the casing.

Thermal shock and thermal stress are induced in tile refractories materials by temperature gradients and thermal expansion characteristics. The amount of stress is proportional to both the gradient and coefficient of expansion. Ideally, a material of high thermal conductivity and low or zero thermal expansion should be applied to burner tiles. Practically, this ideal material cannot be used due to the temperatures encountered in this tile application. Thus, the alloy fiber reinforced castable has been specified to increase the rupture strength of the tile design.

The internally heated burner tile naturally has an I.D. hotter than its O.D. Thus the inner surface will expand more than the outer surface as it is heated. The forces developed by expansion on each concentric section are reactionary. Thus the inner surface is held somewhat in place by the cooler outer concentric areas. The result is a net circumferential

compressive stress on the inside. Conversely, the outer areas are placed in tengential tension by the expanded inner core. Similarly, longitudinal compression stress at the I.D. and tension stress at the O.D. are generated. The failure of a tile is generally believed to originate at the outer surface due to tension in excess of the material ultimate or fracture stress. Refractories are noted for being weaker in tension than in compression. For the case of the burner tile, this can be true even though the compression is generated at higher material temperatures. These higher temperatures are usually associated with lower strengths.

The stress developed in a thick walled unrestrained cylinder of inner radius b and outer radius c, when subjected to a temperature difference ΔT may be expressed as:

$$\sigma \text{ Outer} = \frac{\Delta T \alpha E}{2(1-\nu)\ln(c/b)} \left(1 - \frac{2b^2}{c^2-b^2} \ln \frac{c}{b}\right)$$

$$\sigma \text{ Inner} = \frac{\Delta T \alpha E}{2(1-\nu)\ln(c/b)} \left(1 - \frac{2c^2}{c^2-b^2} \ln \frac{c}{b}\right)$$

ΔT (°F)

α (in/in-°F) = coefficient of thermal expansion

E (lbf/in^2) = modulus of elasticity

ν (unitless) = Poisson's ratio

For the dimensions shown in Figure 1, the above relationships reduce to:

$$\sigma_o = 3.81 \times 10^{-1} \frac{\Delta T \alpha E}{(1-\nu)}$$
$$\sigma_i = 6.18 \times 10^{-1} \frac{\Delta T \alpha E}{(1-\nu)} \quad \text{for 8 1/8" I.D.}$$

$$\sigma_o = 3.38 \times 10^{-1} \frac{\Delta T \alpha E}{(1-\nu)}$$
$$\sigma_i = -6.62 \times 10^{-1} \frac{\Delta T \alpha E}{(1-\nu)} \quad \text{for 6" I.D.}$$

N-2

Data was solicited for the values of E, α and ν. Dr. David Lankard, formerly of Batelle Columbus Laboratories and now president of Lankard Materials Laboratory was contacted. Dr. Lankard has been active in research in fiber reinforced refractory concretes. Dr. Lankard suggested that Mr. Edward Anderson of Babcock & Wilcox Research be contacted. Mr. Anderson has been involved with a Department of Energy contract investigating castable refractories for coal gasification process vessel linings. Material strength and stress evaluations are a part of this program, requiring knowledge of a portion of the desired information for this evaluation.

Mr. Anderson presented the following data for a 90^{+} % tabular alumina material with a CA-25 type cement bond:

$\nu = 0.2$ and independent of temperature

$E = 1.5 \times 10^{6}$ psi @ 250°F

0.5×10^{6} psi @ 500°F

0.75×10^{6} psi @ 2000°F

$\alpha = 5.5 \times 10^{-6}$ in/in - °F for 700°F through 2000°F

(3×10^{-6} for 50% Al_2O_3 material)

Note that this information covers the basic matrix material rather than the wire reinforced material. It is believed that the reinforcing material will not effect these values. The effect is more evident on the crushing strength and/or modulus of rupture. This phenomenon is generally attributed to the crack propagation interference offerred by the ductile fibers.

With knowledge of E, α, and ν, the previous stress relationships can be further reduced. Since most temperatures fall in the 500 to 2000°F range, an average value of 0.625×10^6 psi is applied for the modulus of elasticity.

$$\sigma o = 3.81 \times 10^{-1} \times \frac{5.5 \times 10^{-6} x .625 x 10^6}{(1-0.2)} \Delta T =$$

$$3.81 \times 10^{-1} \times 4.297 \; \Delta T = 1.64 \; \Delta T$$

for 8 1/8" I.D.

$$\sigma i = 6.18 \times 10^{-1} \times 4.297 \Delta T = 0.266 \; \Delta T$$

$$\sigma o = 3.38 \times 15^{-1} \times 4.297 \Delta T = 1.45 \; \Delta T$$

for 6" I.D.

$$\sigma i = -6.62 x \; 10^{-1} \times 4.297 \Delta T = -2.84 \; \Delta T$$

The Wire-N-Cast material applied was nominally 3% wire by weight with a dried density of 143 lb/ft^3. This is roughly equivalent to 1% wire by volume. Wahl publishes values for the hot modulus of rupture as 2843 psi @ 1000°F and 1320 psi @ 2000°F for this material. However, it is believed that these values do not reflect the 1% volume, 330 wire product, but rather an earlier formulation. This belief is based upon the similarity of hot MOR values to those quoted in a 1971 paper by H. Sheets and D. Lankard covering 2 volume % wire of 310 stainless steel. Further, Dr. Lankard conducted the tests for Wahl, and does not recall strength tests on 1 volume % 330 wire.

Data offerred in Sheets' and Lankard's May 1971 American Ceramic Society Paper, attached for reference, offers little on <u>hot</u> strengths. Most

data concerns cold tests on samples after elevated temperature exposure. This data cannot be readily applied in most cases and seems particularly inapplicable to the case of the burner block. Strength at prevailing temperatures is of primary importance. The only hot data in the above paper concerns 2 volume % wire of 310 stainless.

The most applicable data was obtained from Dr. Lankard. Tests were performed on a very similar refractory matrix (alternate manufacturer) and 310 stainless wire. The following strength, i.e., MOR data was obtained for hot tests.

	MOR @ Indicated Temperature (psi)			
Volume % Wire	Room	$1250^{o}F$	$1600^{o}F$	$2100^{o}F$
0	1800	1500	1495	1330
0.5	1770	1510	1380	1180
1.0	2350	2345	1485	1320
2.0	3335	3560	1700	1365

Since tests were conducted on smaller than standard sized specimens, which tends to increase strength, a ratio of strengths was suggested for use. The corresponding 1% volume fiber strength ratios compared to the straight matrix are 1.306 at room temperature, 1.562 at $1250^{o}F$, 0.993 at $1650^{o}F$ and 0.992 at $2100^{o}F$. These ratios are applied to the "plain castable" room temperature and hot modulus data offered in the attached paper. Results are plotted in attached Figure 15. Modulus of rupture values of 1350 to 1900 psi are shown for the reinforced refractory, compared with 1000 to 1200 psi for the basic matrix over the same temperature range. No hot compressive strength data could be located for the fiber reinforced material.

Subsequent discussion in this report will consider stress levels and comparison to strength data. Circumferential and longitudinal O.D. tension stresses will be compared to the hot 310SS MOR data. Compressive I.D. stresses can only be compared to the conventional matrix data, since no other information is available. Fiber reinforcement probably enhances the compressive or crushing strength at lower temperatures. However, as the fiber oxidation and/or the cement bond strength limit is approached, the basic matrix strength probably prevails.

The unrestrained cylindrical stress model is admittedly non-rigorous. Similarly, the degree of accuracy of the strength comparisons is subject to a wide range of variables. The analysis, then is highly theoretical rather than practical. However, the relative nature of improved strengths with fiber reinforcement should prevail. Belief in O.D. tension failure, where fiber can offer the greatest benefit, is continued.

In the following paragraphs, some specifics of each phase of testing will be discussed. In addition to the stresses developed in the simplified model, other data will be reviewed. For reference, it should be noted that fuel oil inputs were derived by the extrapolation method shown in Figure 16. The 400 psig plot is redrawn from the original T-11 calibration curve. Lower inlet pressure levels necessitated the 350 psig inlet curve extrapolation. The method of extrapolation is shown in the figure and was suggested by Mr. Bobzin of Delavan Corp. Values for calculation of % excess air and input were for an average between a straight run and cracked #2 fuel oil. Values used were

138,000 Btu/gal., 7.1 lb/gal, and 1380 scf air/gal. oil for stoichiometry. Air flows were calculated from static and differential pressures and air temperature, assuming ambient pressures of 12.0 psia.

5.1 Pilot Ignition Period

The originally scheduled two hour pilot preheat test was extended to four hours since other system equipment was being repaired. During this period, the pilot input pressures remained fairly constant. Ounce per square inch gages did not allow reading of mixture pressure, as the lower limit of 1 osig was too high for the actual pressure. The pressure drop across the "B-Burner" pilot tip was measured at one point with a manometer. The upstream static pressure was 1.6" w.c. and the zone suction was 1.1" w.c. for a 2.7" w.c. Δ P. The catalog rating for the tip is 52,000 Btu/hr @ 3.5" mixture pressure. The actual input, then, was 52,000 $\sqrt{2.7/3.5}$ = 48,600 Btu/hr.

With reference to Figures 1 and 2, the highest temperature achieved after four hours was 1060°F at T/C #1. This is slightly deceiving since this couple was very close to the pilot port. As the figure shows, a wide range of temperatures resulted, the minimum I.D. temperature being only 320°F at T/C #5 after four hours. Probably more important to operation is the relatively gentle slope of the time-temperature curve. Also, the outer surface of the tile received a 250°F to 300°F

preheat during this period. This preheat reduces the temperature differential across the tile when the main burner is ignited, that is, over a dead cold start. It should be noted that in this and future discussions, temperatures recorded are assumed to be that of the O.D. and I.D. of the tile. This means that extrapolation of temperatures is not attempted to reflect the approximate 1/4" from inner and approximate 1/2" from outer surface location of the thermocouples. The actual I.D. temperature would be slightly higher and the O.D. temperature slightly lower than indicaced.

The maximum stresses during the pilot preheat period would occur at the plane of the pilot and thermocouples 1,2 and 9. The magnitudes are 1300 psi tension and 2100 psi compression. To be noted is the fact that main combustion air flow was very nearly zero during this period. Some small air flow might tend to heat the block more uniformly.

5.2 Main Burner Ignition and One Hour Minimum Fire

During this period, the following average values were determined:

	Burner A	Burner B
Oil inlet press.(psig)	396	386
Oil outlet press.(psig)	93	96
Oil flow (MM Btu/hr)	0.72	0.72
Air ΔP ("w.c.)	4	4
Air static ("w.c.)	negligible	

	Burner A	Burner B
Air flow (scfh)	12,810	12,810
Excess air (%)	78	78
Zone suction ("w.c.)	-2.7	

Light fuel oil combustion products behave somewhat like those of natural gas on a flame temperature basis. Referring to Figure 17, the theoretical flame temperature would be roughly 2550°F for 80% excess air. As Figure 3 shows, the maximum I.D. temperature recorded was 1550°F at T/C #3. Flame temperature is not achieved for several reasons. First, the block and adjacent refractory is a fairly good heat sink at this time. Second, the swirling air flow in the burner may tend to keep a cool air layer against the tile I.D. It is interesting to note that all internal thermocouples now fall within a band of 220°F. Temperatures at the end of 60 minutes had begun to level out in slope. Extended operation would result in increased temperatures, but probably little change in wall thickness ΔT. The maximum ΔT of 1080°F and resultant stress occurs in the plane of T/C's 3 and 8 during the final 10 minutes of the period. Levels calculated are 1800 psi external tension and 2900 psi internal compression.

The pilot preheat period is beneficial in preheating the tile O.D. Low fire oil ignition of a room temperature tile would result in increased ΔT and stress. If the tile I.D. reacted

identically to oil ignition with O.D. temperature commencing at 70^{o}F rather than 270^{o}F, an additional 200^{o}F Δ T would result. The 18.5% increase in ΔT increases stresses to 2100 psi tension and 3400 psi compression.

Figure 15 suggests allowable stresses of 9000 psi compression at the I.D., and 1000 and 1400 psi tension at the O.D., respectively for the basic matrix and reinforced materials. Theoretical tensile strengths are exceeded in both pilot preheated and cold start cases. However, the degree of overstress is substantially reduced for the fiber reinforced material. Later sections of this report discuss possible failures of this type.

5.3 Heating Cycle and Normal Operation

Referring to Figure 5, the heating rates applied can be calculated by determination of the slope of a straight line averaging the temperatures. The following information was derived:

Item	Time Period	Slope-Heating Rate
Afterburner	2 thru 6 hours	100^{o}F/hr
	10 thru 15.5 hours	29^{o}F/hr
	17 thru 19 hours (after shutdown)	115^{o}F/hr
	19 thru 20 hours	30^{o}F/hr
Retort	2 thru 4 hours	60^{o}F/hr
	9 thru 14 hours	40^{o}F/hr

Item	Time Period	Slope-Heating Rate
Retort (cont.)	15.5 thru 18.5 hours (after shutdown)	48^{o}F/hr
	18 thru 18.5 hours	320^{o}F/hr
	19 thru 20 hours	10^{o}F/hr

From the above, it appears that early afterburner heating was twice the intended rate of 50^{o}F/hr. Final heating at approximately 30^{o}F/hr was closer to the desired level. Reheating after the shutdown to repair a pump coupling at approximately 15.5 hours began at 115^{o}F/hr. This is less critical than initial heating at this rate, since the equipment had already seen higher temperatures. Retort heating was nearly always well controlled around the 50^{o}F/hr rate.

Figure 4 shows the burner block temperatures and Figure 7 the excess air and total input levels. The slope of the #1,3,4 and 6 thermocouples in the 2 to 4 hour period are similar at approximately 200^{o}F/hr. This is approximately double the overall afterburner heating rate. After 4 hours, the rate declines until fairly constant temperatures are achieved at about 10 hours. It is interesting to note the difference between temperatures of couples Nos. 1 and 2, and 4 and 5. Couples 2 and 5 are redundancies of 1 and 4, located 90^{o} away. After temperatures had leveled out, the 2 and 5 couples trail the 1 and 4 couples by 200 to 300^{o}F. Evidently the spiral

swirl path of the combustion air or a slightly off-center flame affects this difference.

Table 1 discusses the stresses and strengths of the materials for several times during this period. Data is presented for four planes in the burner. The O.D. temperature for the plane through T/C #6 is taken as afterburner zone temperature. The compressive stresses on the tile I.D. appear to fall below the compressive strength of the basic material. Tension stresses on the tile O.D., however, are substantial. MOR strength of the basic material is exceeded in nearly all cases, often by more than 100%. Hot MOR strengths of the wire reinforced product are also exceeded but by a lesser degree. A 33 to 47% over-stress occurs in the plane of T/C's 1,2 and 9. In the plane of T/C's 3 and 8, 0 to 9% over-stress occurs, i.e., to a very minor degree. In other planes, the maximum stresses are below the strength values. The maximum deviation from allowable tensile stress occurs at the external surface, rather than at some sub-surface point. This was found to be true for several cases checked by plotting a linear stress distribution versus temperature related strength. This is true because the slope of the radial stress distribution is greater than the slope of the temperature related strength. An example is shown in Figure 18. Of interest is the fact that excess stress is noted in only a small region near the outer surface of the tile.

During the heating cycle, the maximum stresses occur in the plane outside the furnace wall. The maximum internal temperature is generated in this area. Heat losses are also a maximum from the outer shell. The net result is a maximum Δ T and related stress. Fracture in this area may not provide problems, if the cracks do not propagate longitudinally towards the slagging afterburner I.D. If the tile is sealed to the metallic housing, no differential pressure would exist to cause hot gas movement through the crack(s). Further, surface failures may not propagate to the tile I.D. due to effects of the wire.

At the end of the heating cycle, the "B-Burner" operated at 55 to 60% excess air. The flame temperature at this level is approximately 2750°F. The maximum internal block temperature falls within approximately 500°F of the source temperature at equilibrium. It is certainly possible that a higher internal temperature exists at another unmonitored point. Therefore, it appears that the past practice of specifying materials compatible with anticipated flame temperature is justified.

The worst possible case for the tile would be an instantaneous ignition at high fire where I.D. temperatures reached flame temperature with a cold I.D. The 2700°F ΔT would result in 7650 psi compression at the 6" diameter exit port and 4450 psi tension at the outer surface of the 8 1/8" diameter section.

These extreme stresses seem beyond the strengh of nearly any conceivable refractory. The importance of slow heating is emphasized for the burner tile and also adjacent refractory.

Towards the end of the heating cycle, i.e., nearing equilibrium, velocity surveys were conducted. The following information was reported.

Location	Flow(scfm)	Temperature($^{\circ}$F)
Slots under double tipping valve	63	195
Retort burner end infiltration	375	185
Retort burner combustion air	904	170
Effluent gas flow	4153	455

The afterburner achieved a zone temperature of 1450°F and may have achieved possibly 1500°F given extended time. It is understood that the original design called for heating of 3000 scfm from 1100 to 1600°F. When the afterburner temperature was 1450°F, the effluent gas temperature was 720°F, or a 730°F temperature rise was achieved. If the flow were reduced to the original 3000 scfm, the Δ T achieved would be 730 x $\frac{4153}{3000}$ x $\frac{\text{Av.Ht.@ }1600^{\circ}\text{F,50\% Ex.Air}}{\text{Av.Ht.@ }1450^{\circ}\text{F,50\% Ex.Air}}$, or 730 x $\frac{4153}{3000}$ x $\frac{.42}{.47}$ = 903°F. Thus the existing system would yield 903 + 720 = 1623°F temperature at wide open conditions with the 3000 scfm flow. When actually processing munitions, the effluent temperature would be great

enough to provide at least 1600°F, even at the 4100 scfm rate. For either case, the afterburner input would decrease somewhat from maximum to maintain 1600°F.

5.4 Power Failure and Related Shutdown and Relight Period

Two short-term power outages were simulated to observe temperature effects on the tile. Originally three tests were planned, but two seemed adequate within the time schedule. The shutdown and slow reheat during the heating cycle was to be additionally analyzed as a third point. Burner block data for this period was not complete, however, as repair of sluggish chart recorder action was attempted.

Both tests were to reflect a power shutdown with rapid recovery. Relighting during the first failure was somewhat delayed. Cleaning of afterburner U.V. cell lenses was required, plus the time to locate the problem. Evidently a faulty low combustion air pressure switch had not shut down the after burner oil flow in the earlier repair shutdown. Deposits on the cells blocked adequate transmission of the pilot signal, preventing main burner light off. This condition is potentially unsafe and must be corrected, as oil could be added in the absence of air and an ignition source.

Flame or power failure brings about a unique set of conditions. The required purge cools the block I.D. substantially, as shown in Figures 8 and 9. Comparing the two figures, the multiple

purges occuring during the first outage cooled the block ID to as low as 680°F. The second failure showed a minimum temperature of 1180°F for a single purge and successful relight. Both minimum temperatures occurred at the 6" diameter discharge port.

Under the purge condition, the burner block I.D. is cooled below the temperature of surrounding material. The inner surface is placed in tension. In addition, the inner surface area no longer has the benefit of added strength from the fiber reinforcement. The basic matrix strength prevails, since the inner fibers have been heated beyond their oxidation temperature and/or strength limit. Possibly even local fiber melting has occurred and subsequently weakened the basic matrix material.

To examine the conditions during purge, a computer model was generated for the tile. The initial temperature profile and an incremental heat balance on each of 10 radial thickness elements was applied. The inner and outer surface temperatures were taken from the chart recorder. Assuming 42,000 scfh air flow at 40" w.c. Δ P and 34" static, a convective heat transfer coefficient of 5.6 was calculated from the relation $h_c = 0.322\ V^{0.8}/\text{I.D.}^{0.2}$. This coefficient and 100°F wind temperature were used to calculate the temperature profiles after 1/8, 1/4, 3/8 and 1/2 hours of purge. Results are presented in Figure 19, for the plane through thermocouples 1,2, and 9.

As Figure 19 shows, cooling is affected in only a narrow zone adjacent to the inner diameter. The tension due to the cooling is also applied in this very small zone. The stress on a thin cylinder subjected to differential temperature is equal to 1/2 $\frac{E\alpha\Delta T}{(1-\nu)}$. Applying this to the thin inner section of 0.22 inches radial thickness, the maximum 1250°F ΔT after one half hour cooling results in 2700 psi stress. The stress is tension at the inner surface and compression at the outer surface. Applying a 1200°F ΔT to the thick outer section, 3150 psi compression would occur at 4 1/16 + 0.22 = 4.28" with 2000 psi tension at the external surface. Superimposing the two stress levels at the 3150 psi compression level of the more massive outer section has the effect of subtracting 3150-2700 = 450 psi tension from the innermost tile surface. The tension stress would then be 2700-450 = 2250 psi at this inner surface. Clearly this is beyond the strength of the basic refractory material and some internal cracking and spalling would be expected. It is important to note, though, that this happens only in a very thin inner section and cracks would probably not propagate to the outside. This is believed true due to the enduring compression zone beyond the tensile layer. There seems no way to guard against the occurrance of inner tension during purge of a hot tile, either by design or process change. In addition, sizeable external tension still exists on the tile section outside of the furnace wall.

Some additional crack propagation is possible from a phenomenon known as "racheting". Small internal cracks can become filled with dirt at cold conditions. Subsequent reheating and expansion around the now-filled voids tends to add stress and extend cracks. Again, it is felt that the wire reinforced refractory should show improved performance under continued cycling with this condition.

5.5 Cooling Cycle

Stress levels and damage to the refractory should be minimal during the cooling cycle. During the first seven hours, adjustments to input were slow with I.D./O.D. temperature gradients and resultant stresses decreasing. Adjustments were slow such that probably very little tension stress, if any, would be developed at the tile I.D. That is, I.D. surface temperatures would continue to be greater than adjacent material temperatures.

The afterburner was shutdown approximately 7 hours into the cooling cycle by the operator. It is understood that this was according to an outdated S.O.P. While not as severe cooling shock is applied as in the hot purge condition, some internal tension is probably generated. Continued slow cooling to afterburner minimum fire would not add any additional time to the cooling cycle. And, since operators must be present to supervise retort cooling, continued afterburner cooling is a minor addition. Therefore, it is recommended that the

November 30, 1977, S.O.P. No. OPN 04-00-01-05 be followed.

While stress levels are not great, failures are probably related to the number of cycles at a given stress level, from a fatigue point of view. This cooling time seems ideal for minimization or elimination of an added stress cycle.

6. CONCLUSION

Throughout this report, tile conditions as a result of environment have been discussed. Increased strengths of the wire-reinforced material have been shown to exist. Specific information for the exact materials applied was regretably unavailable. The theoretical tensile strength (MOR) of even the wire reinforced material was exceeded in several cases. Several ideas come to mind as possible corrective actions. The general nature of these ideas are explored in the following paragraphs.

The primary factors affecting stress levels are the temperatures, coefficient of expansion, and geometry. Little can probably be done to alter the modulus of elasticity or Poisson's ratio for refractory type materials. Strength is related to materials, temperature, and reinforcement technique.

Reduced stress levels can be achieved by application of lower expansion rate materials. The zero expansion type materials seem to be ruled out by their hot face limit of about $2000^{o}F$. However, a lower percentage alumina castable might be considered. For example, a 50% Al_2O_3 castable has a thermal expansion coefficient of 3×10^{-6} in/in-^{o}F, per Mr. Anderson of B&W. Comparing this to the 5.5×10^{-6} value for the 90+% Al_2O_3 matrix, one would expect a 45% reduction in stress level for identical temperatures. Further hot strength data for conventional and reinforced lower alumina castables should be investigated before application. In general, however, lower expansion rate materials would result in lower stress levels.

Similarly, higher thermal conductivity in the castable would seem beneficial. The reduced ΔT would correspondingly reduce the stress levels. This effect can also be achieved by increasing the insulation level adjacent to the burner tile. Both of these items must be considered quite carefully before application. Higher mean or surface temperatures can offset the benefits of lower stresses. This is true since the refractory and especially reinforced refractory strength is an inverse function of temperature.

Increased insulation value or reduced heat loss from the exposed portion of tile should be considered. This portion of the tile exhibited consistently high O.D. tension stress. As discussed earlier, this is a result of high internal heat generation and high external heat loss. The high differential temperature and stresses are to be expected with the exposed burner tile section. Most conventional burners avoid or minimize these effects by placement of the entire tile within the furnace wall. This is unfortunately very difficult to accomplish with the existing pilot and scanner locations. External insulation of the tile housing is similarly difficult due to the temperature limit of the carbon steel shell. Internal rigid shell insulation or external insulation of an alloy housing seem the only practical possibilities. Another advantage of more uniform external (and internal) temperatures would be to minimize shear stress. A tension component as a result of shear can be evident even in a general state of compression.

The final area for possible improvements lies in the application of the

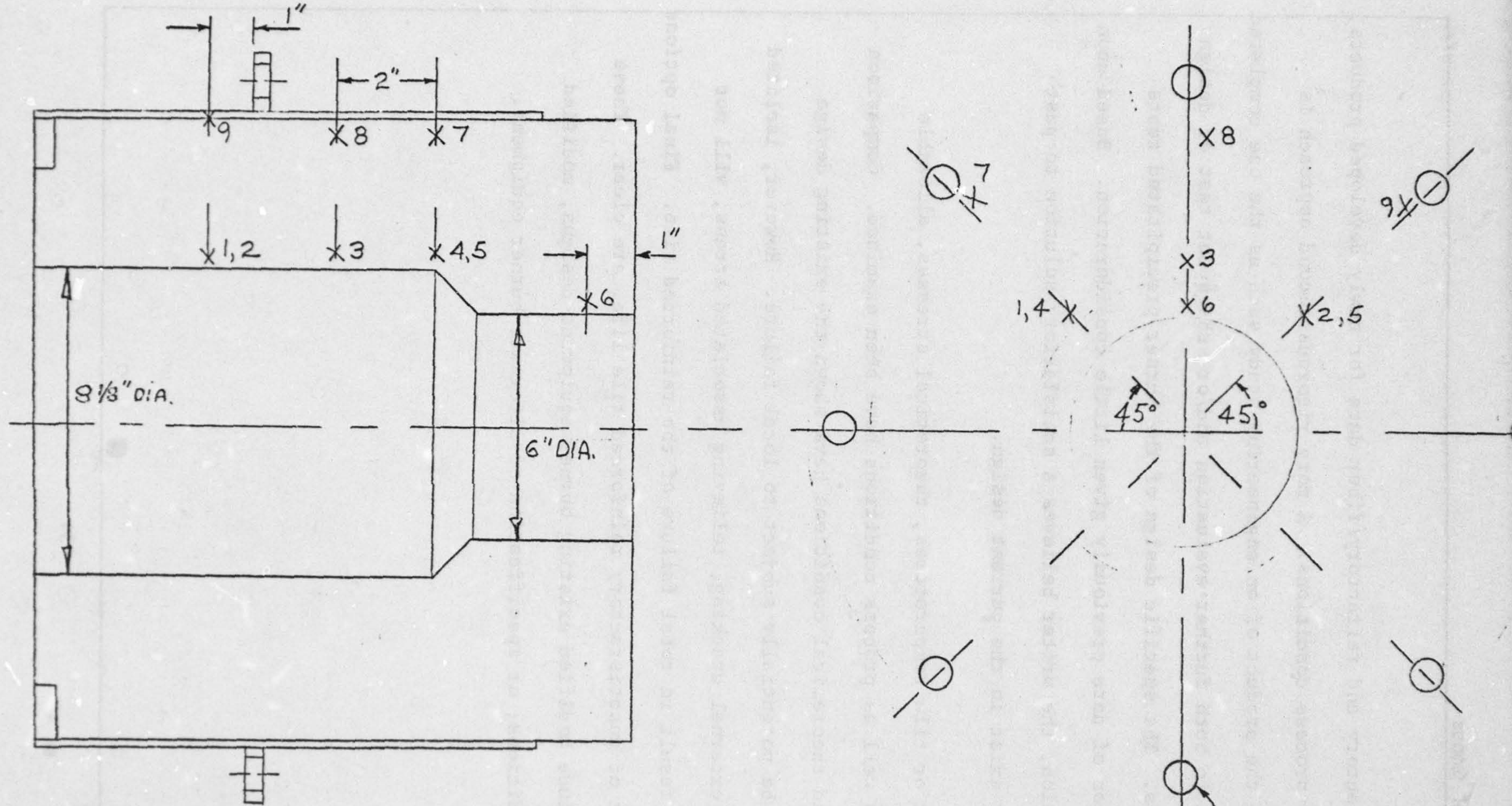
fibers themselves. The comparison all along has been to the available data for 1 volume % 310 stainless steel fibers. It is now known what improvements are offerred by 330 wires over basic oxidation resistance at elevated temperatures. One new product was discovered during information gathering for this report. Dramix[R] fibers are being marketed by Bekaert Steel Wire Corporation. Several types of "hooked" fibers are offerred claiming improved results over conventional straight fibers. Dr. Lankard has stated that Wahl Refractories is expected to begin marketing of castables with the Dramix fibers. No technical information relating to high temperature strength in refractories could be located, however. Information has been attached for reference, should this become a future consideration. Increased wire weight or volume percentage should also be considered for any modified design.

For the present, it appears that the reinforced tiles have survived this first firing. Mr. Norm Jarrett reported that inspection of the tiles after shutdown showed only several hairline cracks at the I.D. after this test program. Only continued operation can determine if satisfactory life has been attained. Certainly small cracks should not effect operation. Complete radial crack failure in the longitudinal or the transverse direction would necessitate further application engineering. The excess stress predictions may, in fact, result in some surface cracking failures, but the added strength of the metallic/ceramic combination may prevent the complete failure of the tile for extended periods of time.

In final thought, extended evaluation of the existing data may be possible. The basic information could be applicable to advanced stress

models, refractory and refractory/fiber data for newly developed products, and modified process conditions. A more rigorous second approach is consistently the product of an engineering study such as the one completed. This is true in both further evaluation and/or subsequent test or design opportunities. The specific design of the burner precipitated tests and discussion of data previously given little consideration. Based upon this evaluation, the writer believes a satisfactory solution to past problems may exist in the current design.

Burner block or tile temperatures, theoretical stresses, allowable stresses, as well as process conditions have been examined. Comparison of actual and theoretical conditions have shown the existing design material to be potentially subject to local failure. However, isolated internal or external cracking, relieving associated stress, will not necessarily result in total failure of the reinforced tile. Final options in the event of unsatisfactory reinforced tile life, are clear. These options include modified existing burner equipment designs, modified process conditions, or specification of alternate burner equipment.



Notes: All ID couples 3/8" from inside surface.
All OD couples 1/2" from outer surface.
All couples cemented in preformed holes with Adamant.
Holes to be cast in shape.

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66760

Figure 1

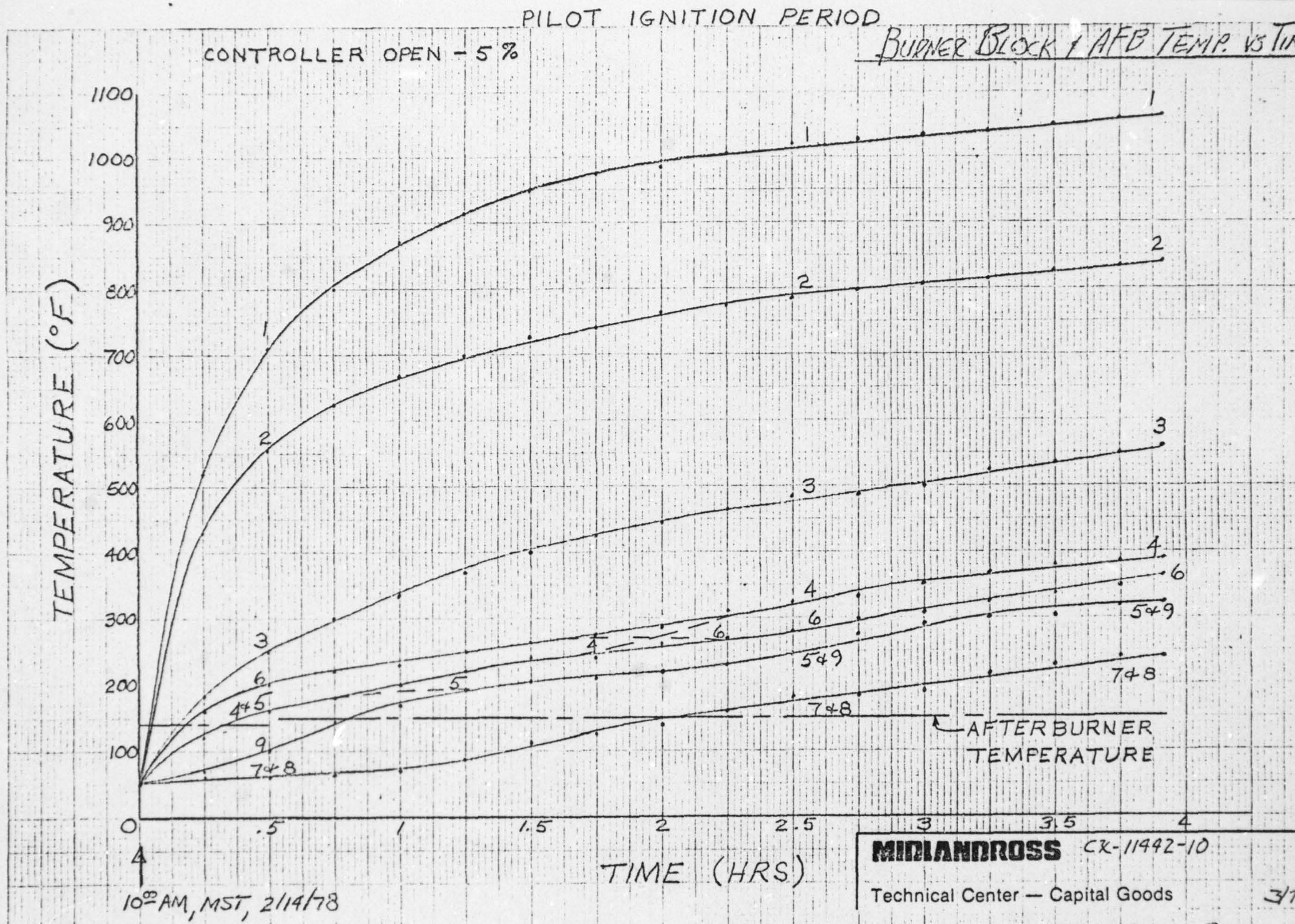

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FIGURE - 2

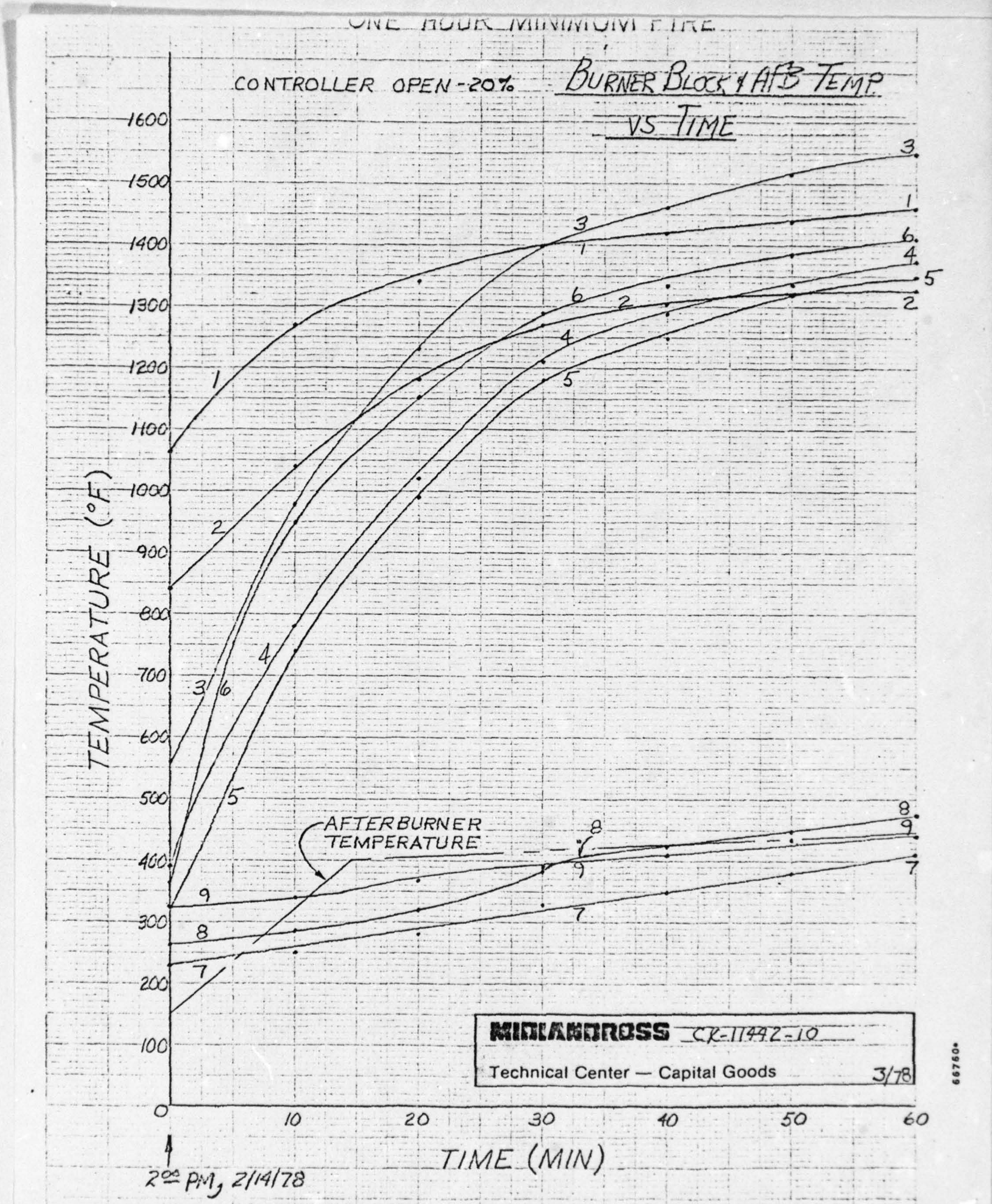

ONE HOUR MINIMUM FIRE
CONTROLLER OPEN -20%
BURNER BLOCK & AFB TEMP. VS TIME
TEMPERATURE (°F)
TIME (MIN)
AFTERBURNER TEMPERATURE
2:00 PM, 2/14/78
MIDLANDROSS CR-11442-10
Technical Center — Capital Goods 3/78
66760

FIGURE -3

K+E 10 X 10 TO ½ INCH 47 1323

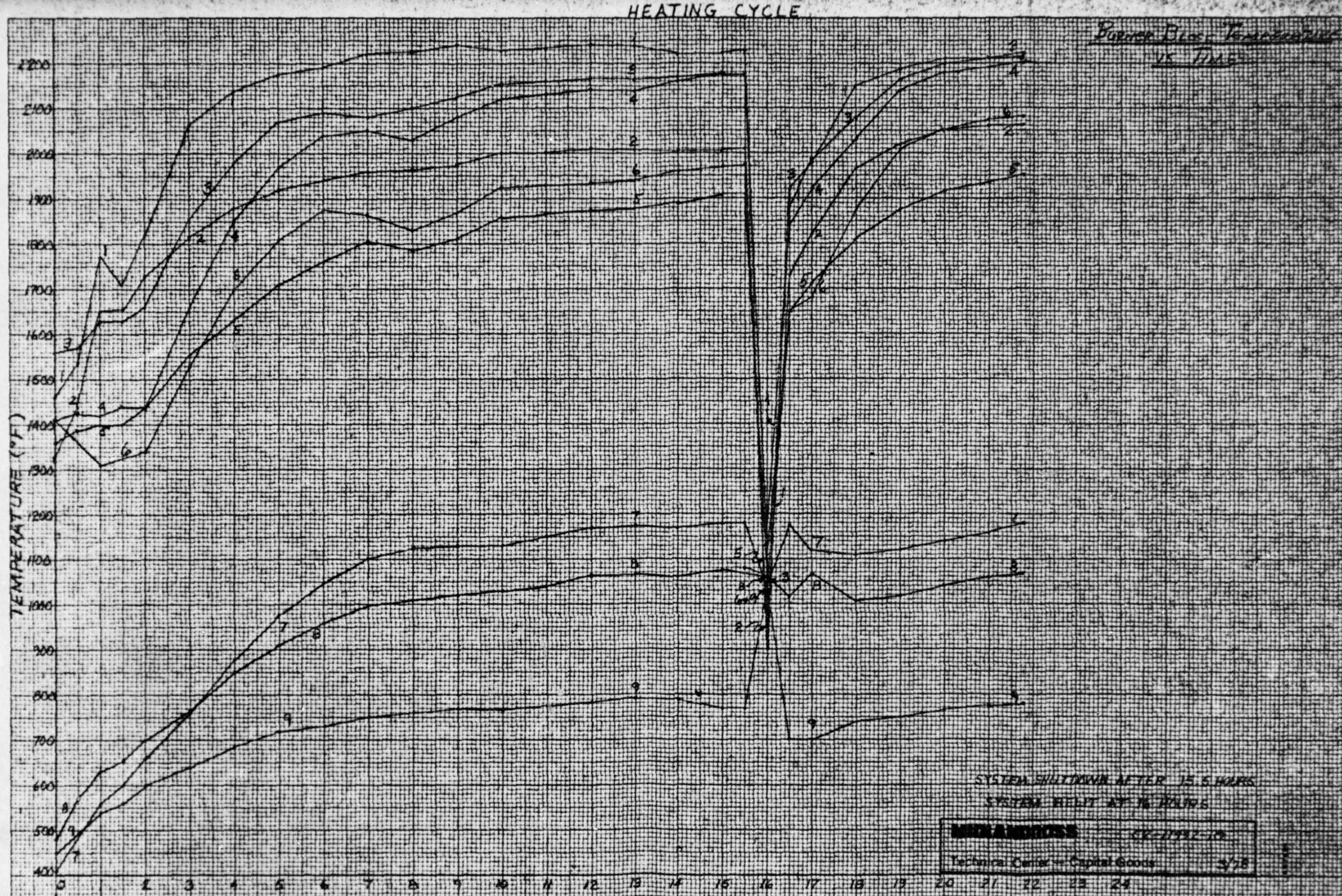


FIGURE - 4

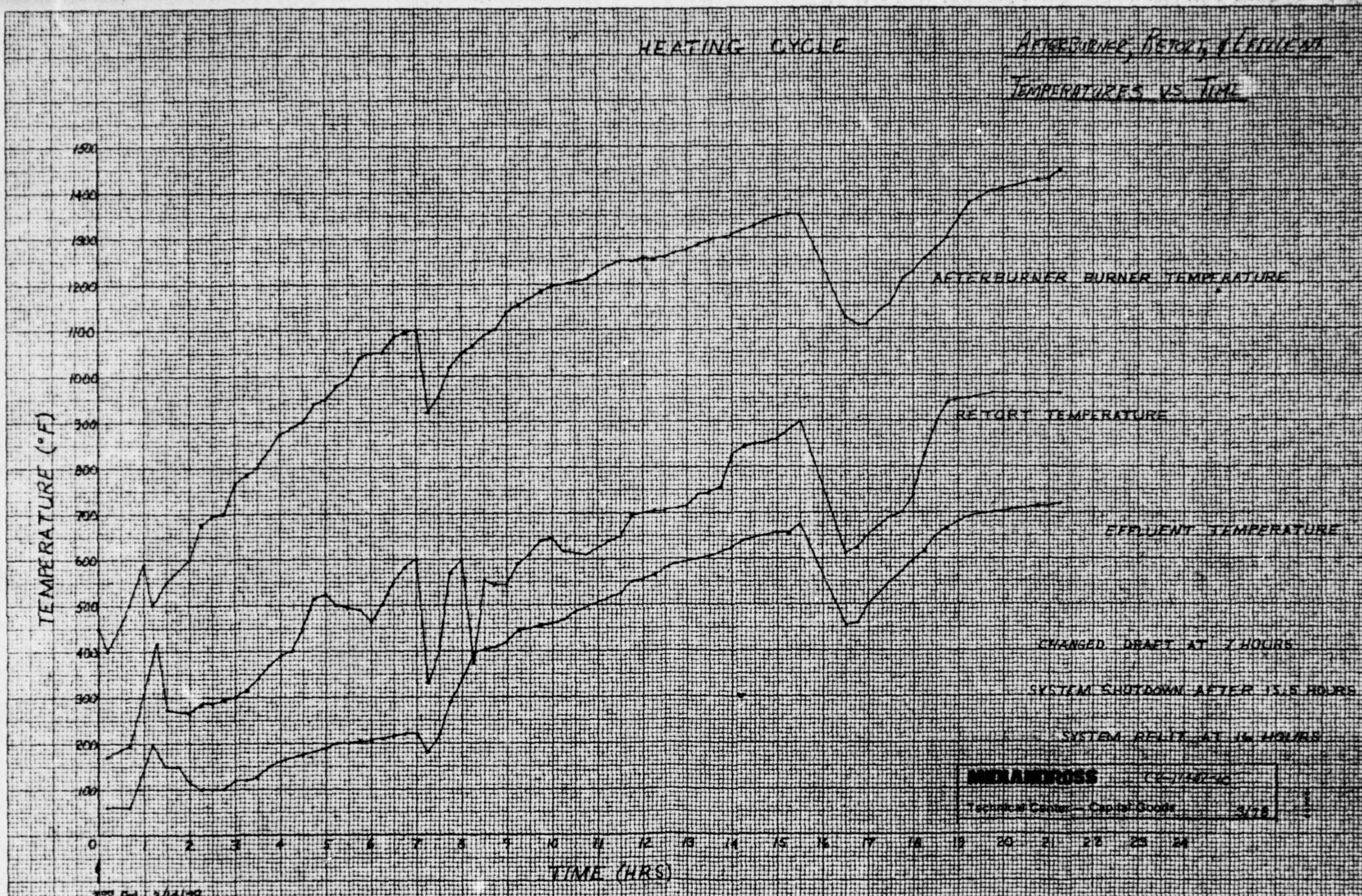
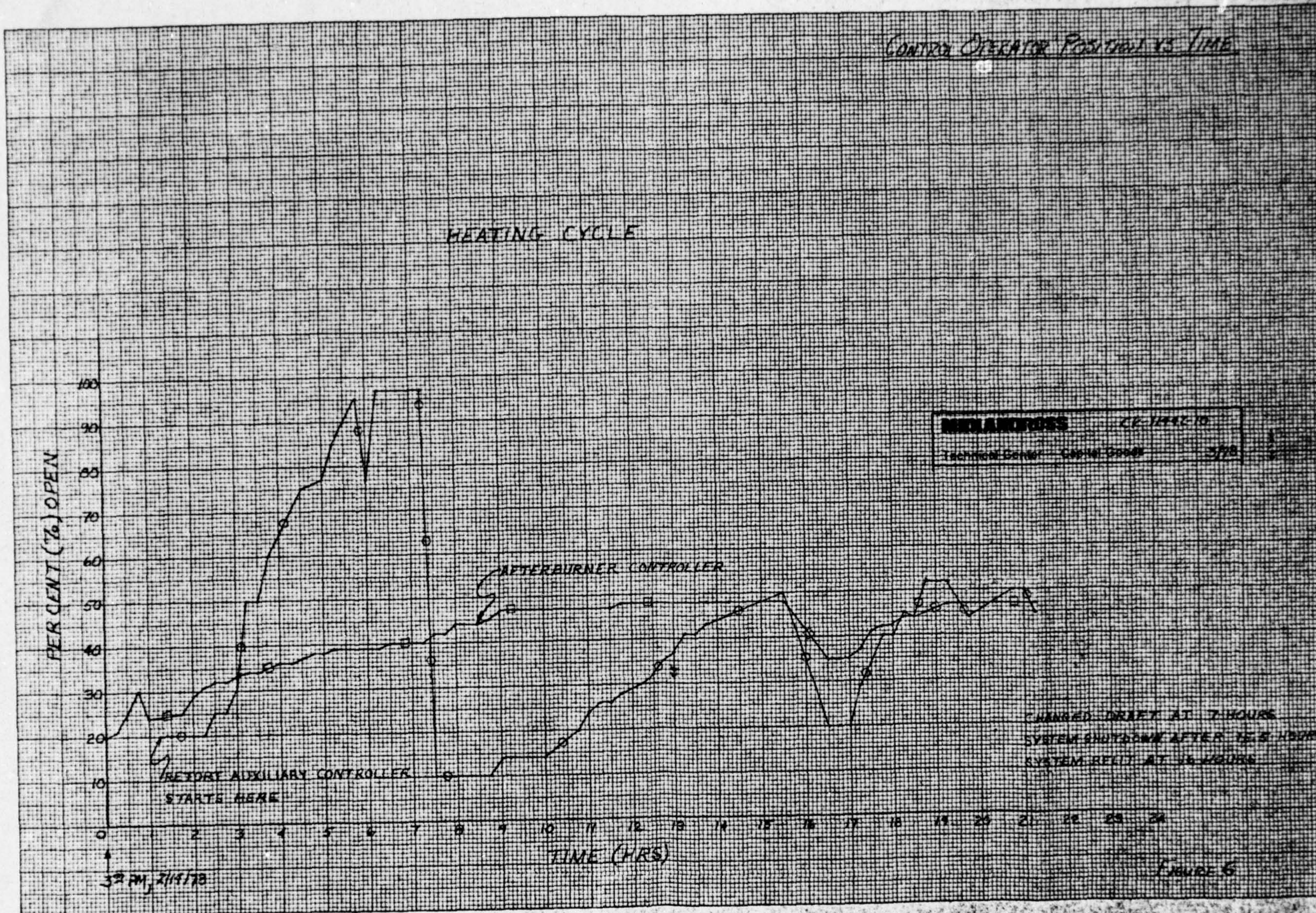
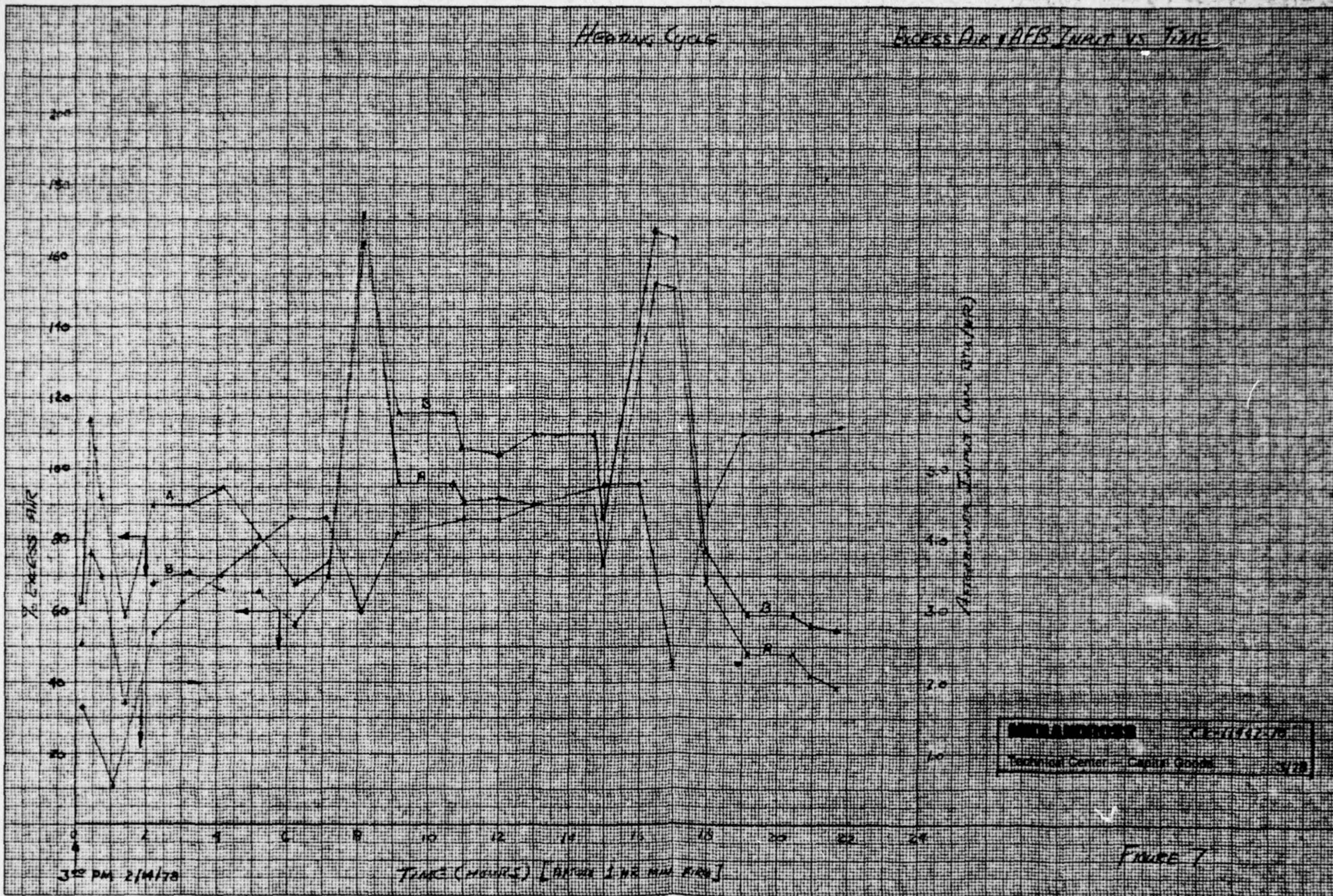

HEATING CYCLE
AFTERBURNER, RETORT, & EFFLUENT
TEMPERATURES VS TIME
TEMPERATURE (°F)
TIME (HRS)
AFTERBURNER BURNER TEMPERATURE
RETORT TEMPERATURE
EFFLUENT TEMPERATURE
CHANGED DRAFT AT 7 HOURS
SYSTEM SHUTDOWN AFTER 15.5 HOURS
SYSTEM RELIT AT 16 HOURS
Technical Center — Capital Goods
3/78
3:00 PM, 2/14/78

FIGURE 5

K·E 10 X 10 TO ½ INCH · 10 X 15 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A. 47 1323





HEATING CYCLE
EXCESS AIR & AFB INPUT VS TIME
% EXCESS AIR
TIME (HOURS)
3 PM 2/14/78
[redacted]
Technical Center — Capital Goods

FIGURE 7

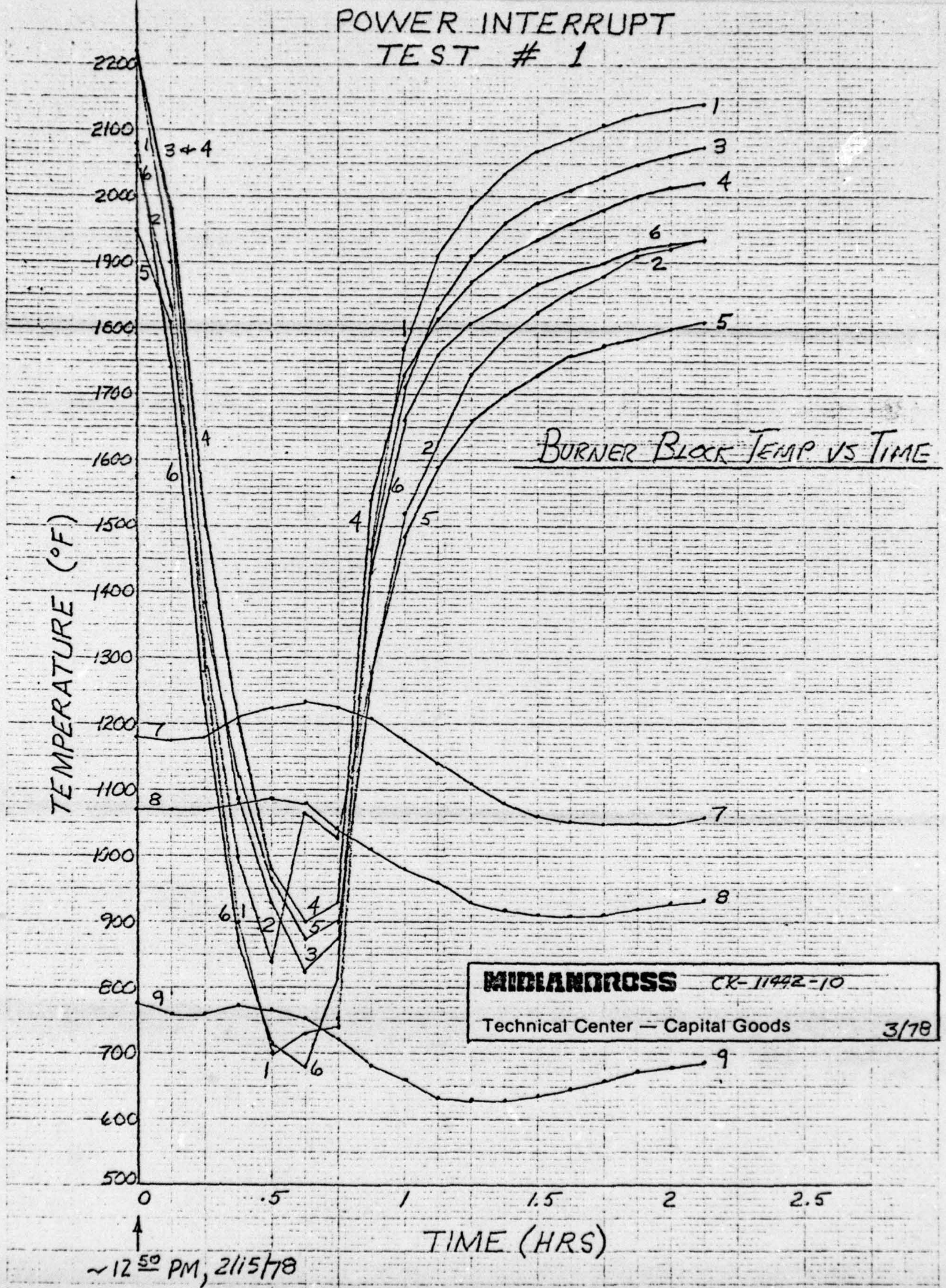

POWER INTERRUPT
TEST # 1
BURNER BLOCK TEMP VS TIME
TEMPERATURE (°F)
2200
2100
2000
1900
1600
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
0
.5
1
1.5
2
2.5
TIME (HRS)
~$12^{\underline{50}}$ PM, 2/15/78
MIDLANDROSS CK-11442-10
Technical Center — Capital Goods 3/78

FIGURE - 8

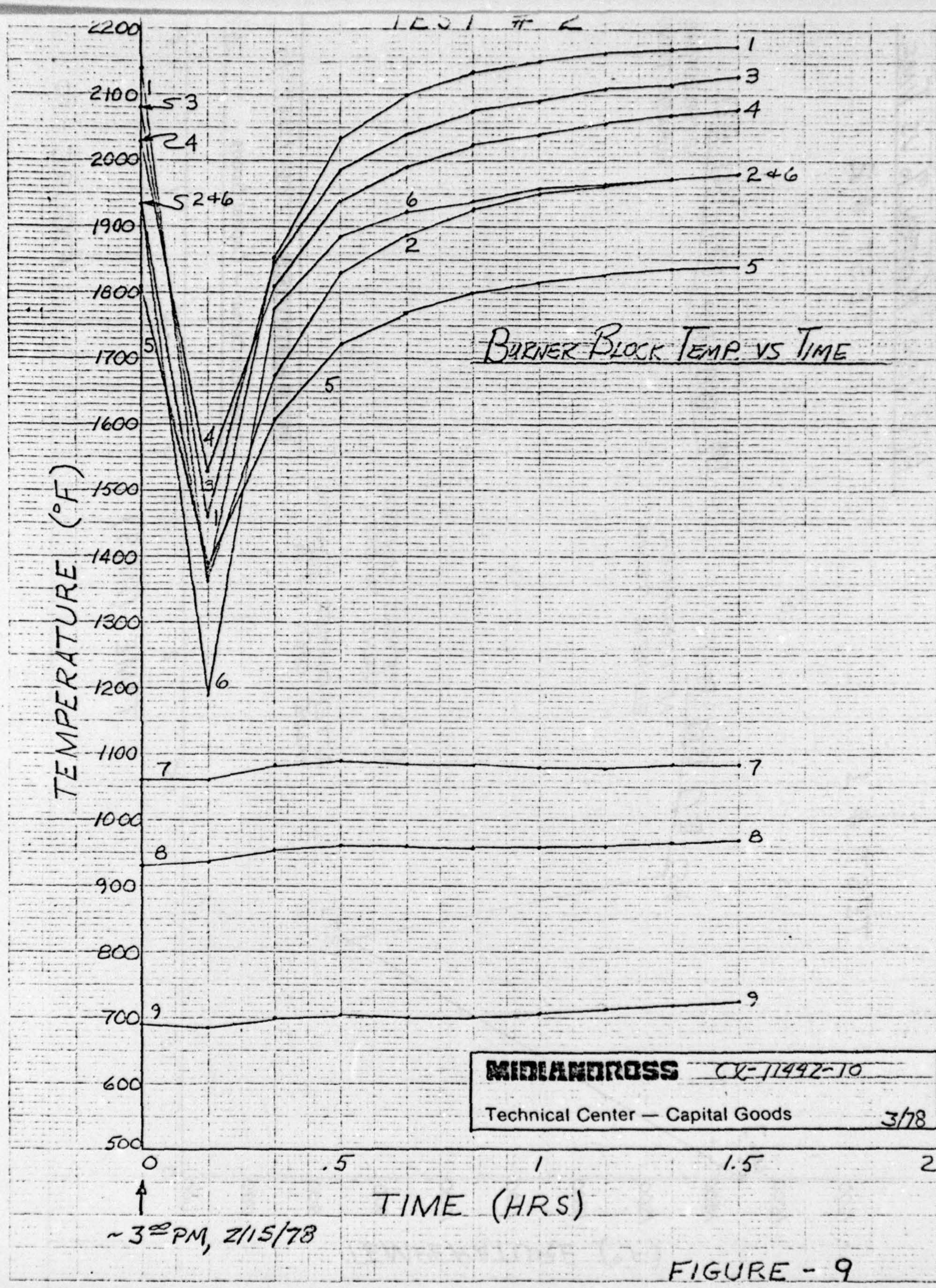
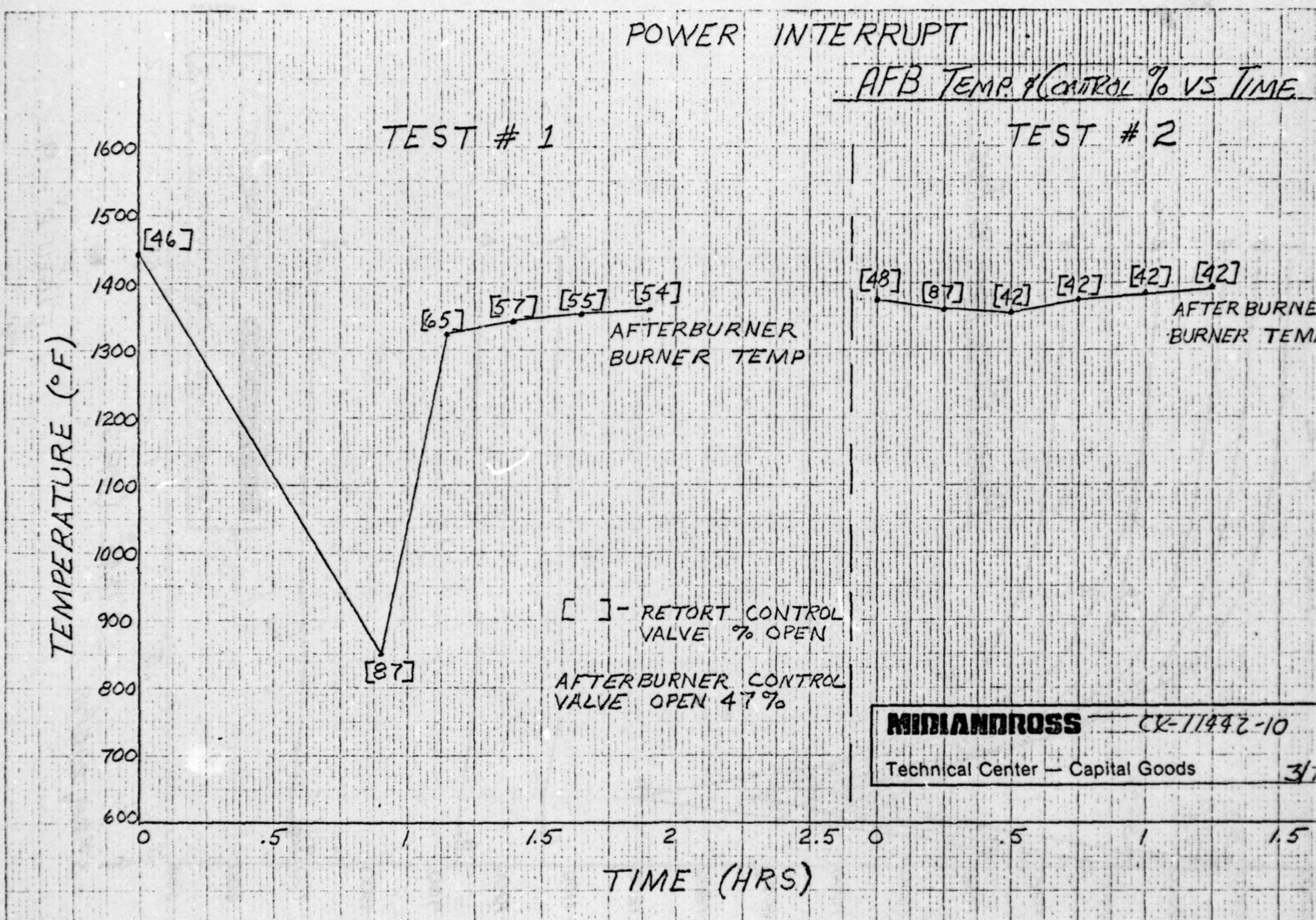

TEST # 2
Burner Block Temp. vs Time
TEMPERATURE (°F)
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
1
3
4
2+6
6
2
5
7
8
9
0
.5
1
1.5
2
TIME (HRS)
~3ºº PM, 2/15/78
MIDLANDROSS CX-11492-10
Technical Center — Capital Goods
3/78
66760

FIGURE - 9



POWER INTERRUPT
AFB TEMP & CONTROL % VS TIME
TEST # 1
TEST # 2
TEMPERATURE (°F)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
[46]
[87]
[65]
[57]
[55]
[54]
AFTERBURNER BURNER TEMP
[ ] - RETORT CONTROL VALVE % OPEN
AFTERBURNER CONTROL VALVE OPEN 47%
[48]
[87]
[42]
[42]
[42]
[42]
AFTERBURNE BURNER TEMP
0
.5
1
1.5
2
2.5
0
.5
1
1.5
TIME (HRS)
MIDLANDROSS CK-11442-10
Technical Center — Capital Goods
3/7

FIGURE - 10

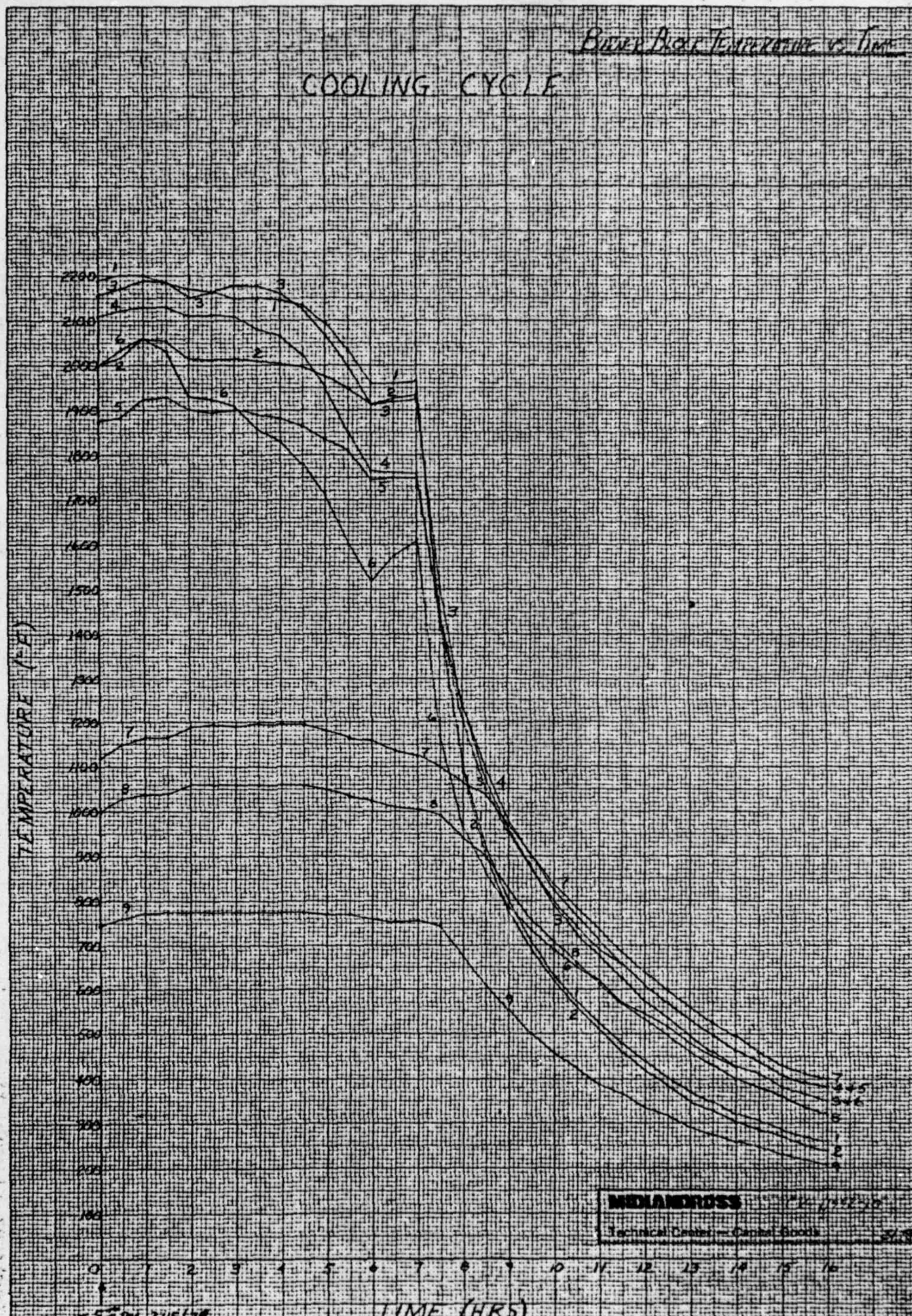
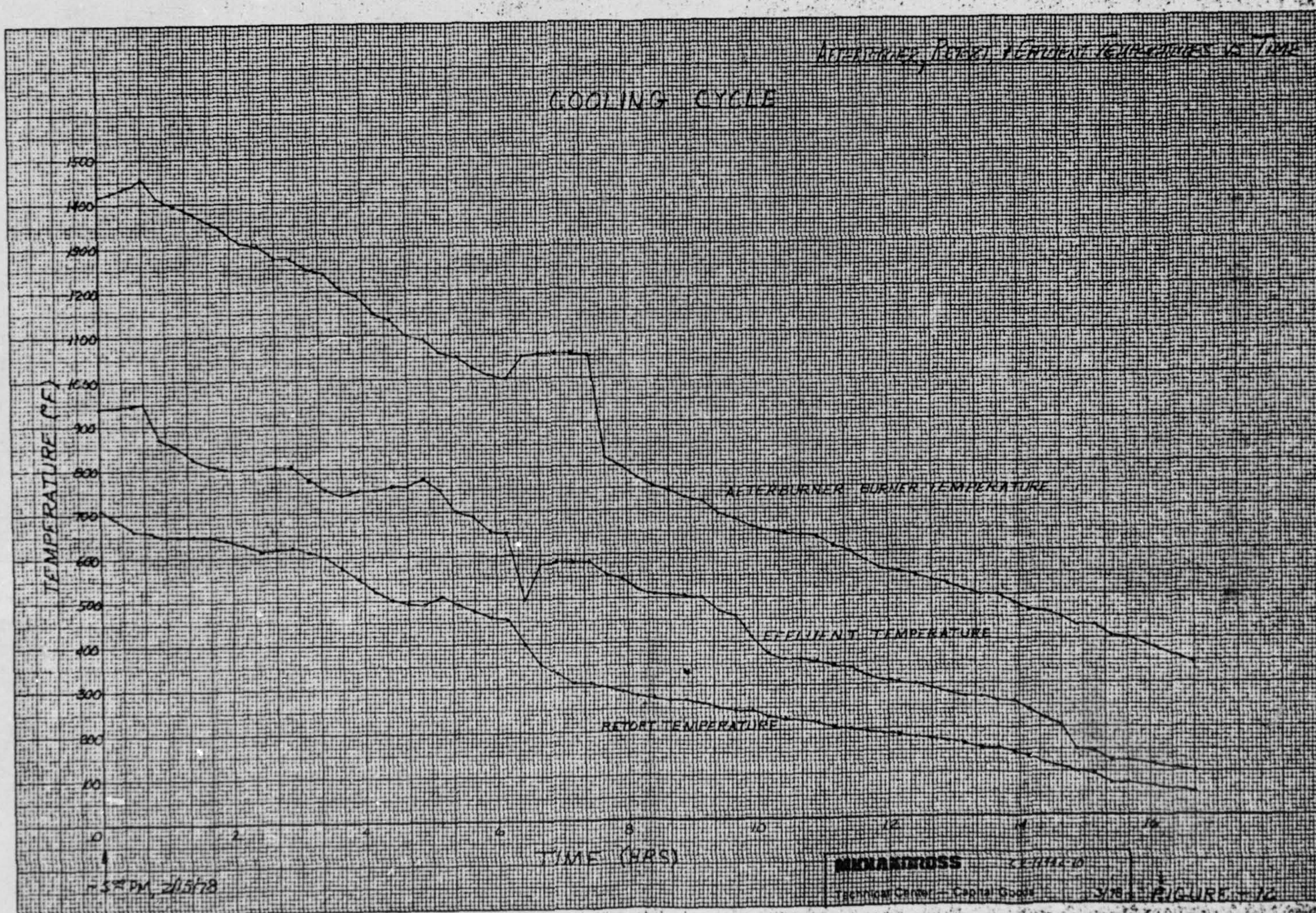

COOLING CYCLE
TEMPERATURE (°F)
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
TIME (HRS)
MIDLANDROSS
Technical Center — Capital Goods

FIGURE - 11



AFTERBURNER, RETORT, & EFFLUENT TEMPERATURES vs TIME
COOLING CYCLE
TEMPERATURE (°F)
TIME (HRS)
AFTERBURNER BURNER TEMPERATURE
EFFLUENT TEMPERATURE
RETORT TEMPERATURE
~3 PM, 2/15/78
MINNEAPOLIS
Technical Center — Capital Goods
FIGURE 12
47 1323
K+E

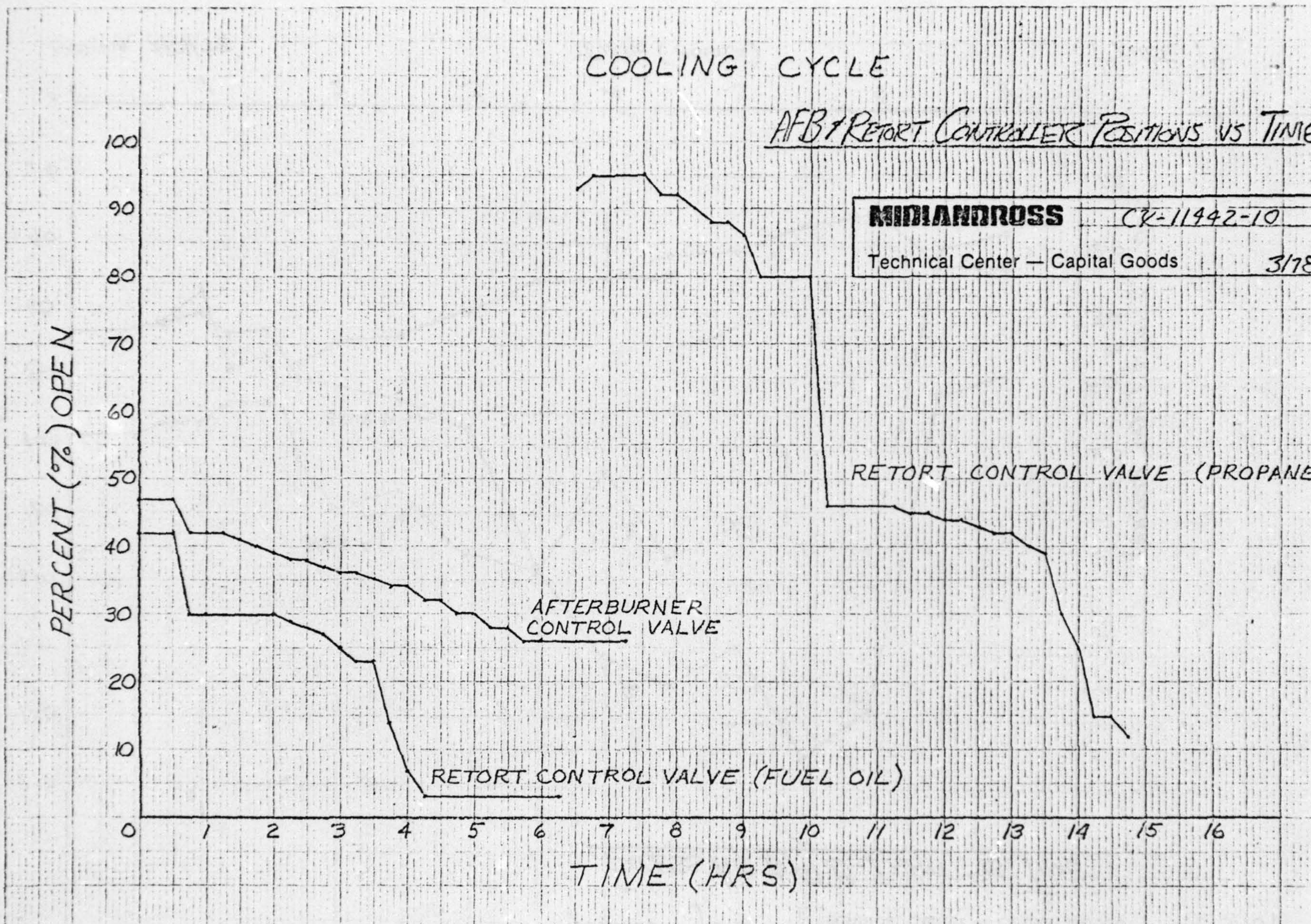

COOLING CYCLE
AFB & RETORT CONTROLLER POSITIONS VS TIME
MIDLANDROSS CK-11442-10
Technical Center — Capital Goods 3/78
PERCENT (%) OPEN
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
TIME (HRS)
RETORT CONTROL VALVE (PROPANE)
AFTERBURNER CONTROL VALVE
RETORT CONTROL VALVE (FUEL OIL)

FIGURE -13

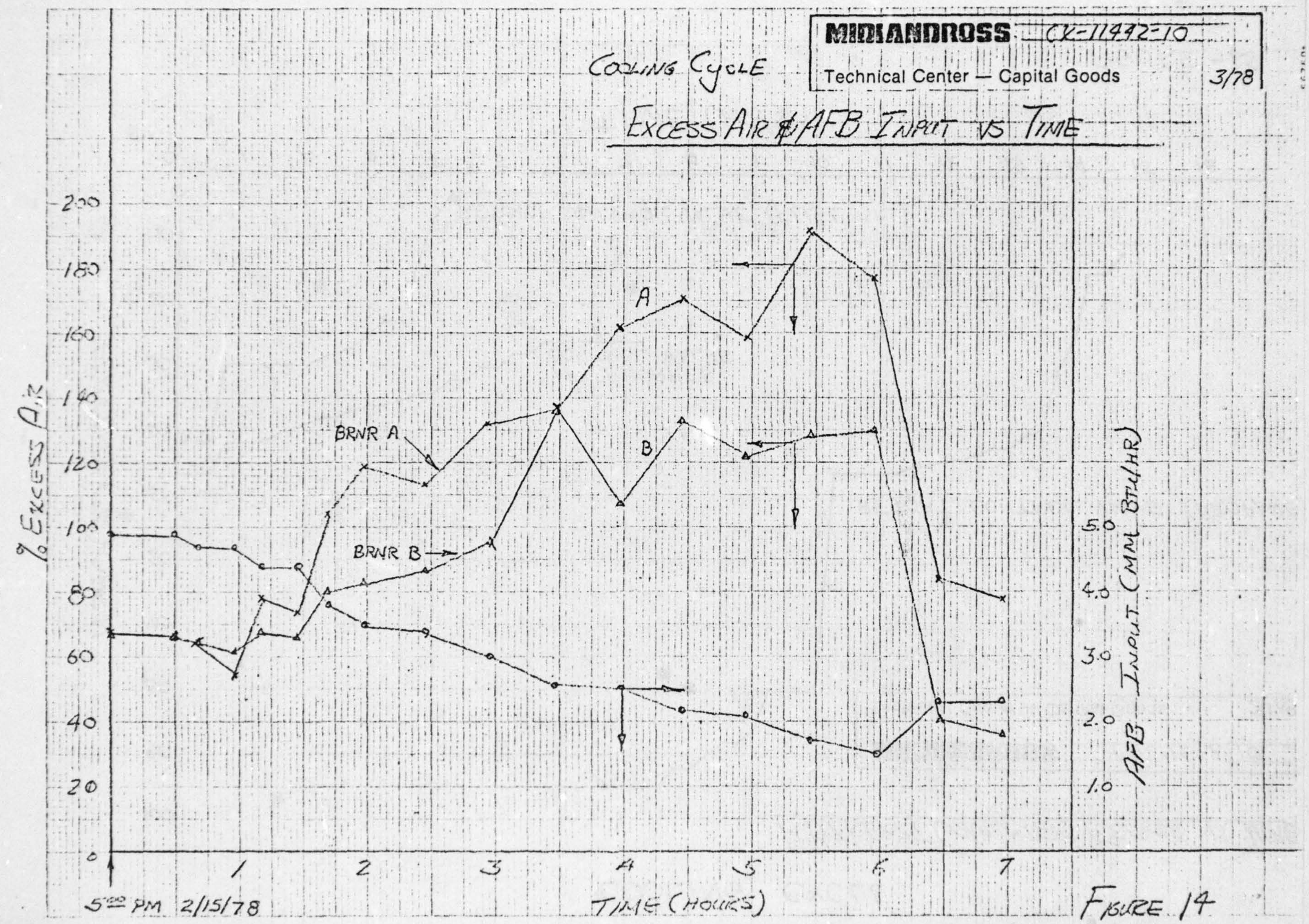

MIDLANDROSS CX-11492-10
Technical Center — Capital Goods
3/78
COOLING CYCLE
EXCESS AIR & AFB INPUT VS TIME
% EXCESS AIR
200
180
160
140
120
100
80
60
40
20
0
A
B
BRNR A
BRNR B
5.0
4.0
3.0
2.0
1.0
AFB INPUT (MM BTU/HR)
1
2
3
4
5
6
7
5:00 PM 2/15/78
TIME (HOURS)

FIGURE 14

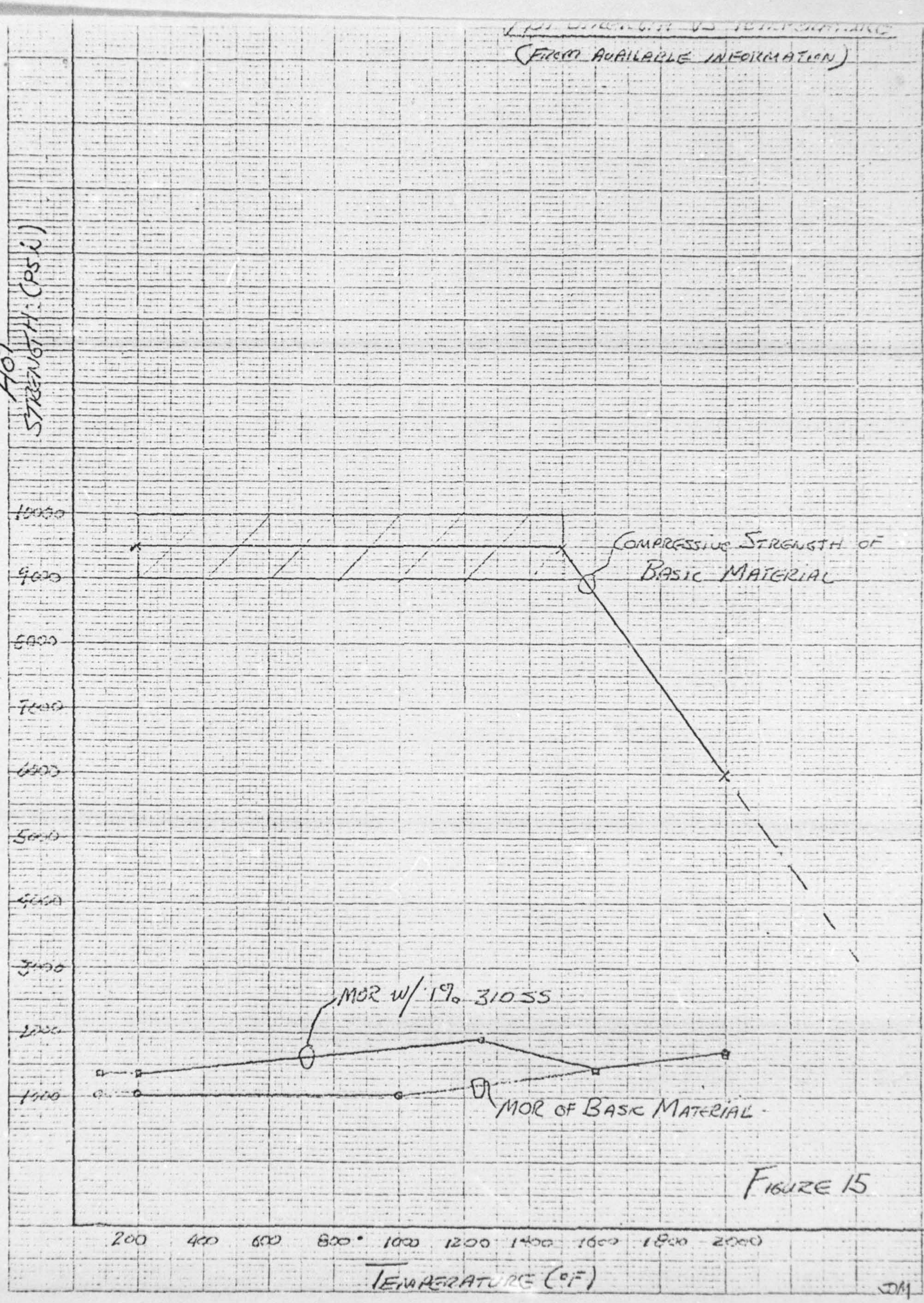

(FROM AVAILABLE INFORMATION)
HOT STRENGTH (PSI)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
COMPRESSIVE STRENGTH OF BASIC MATERIAL
MOR W/ 1% 310 SS
MOR OF BASIC MATERIAL
200
400
600
800
1000
1200
1400
1600
1800
2000
TEMPERATURE (°F)
DM

FIGURE 15

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM. KEUFFEL & ESSER CO. MADE IN U.S.A. 47 1513

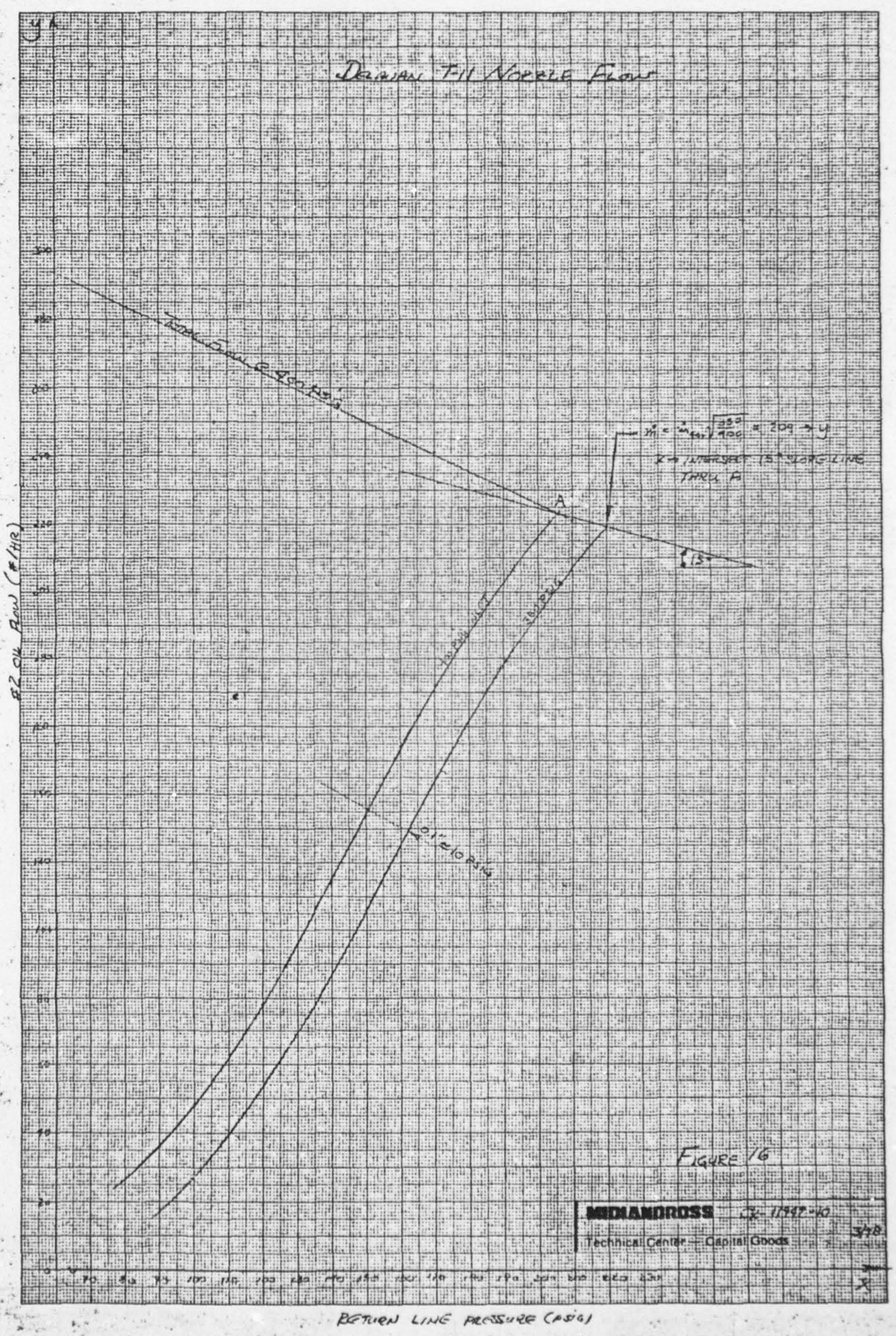
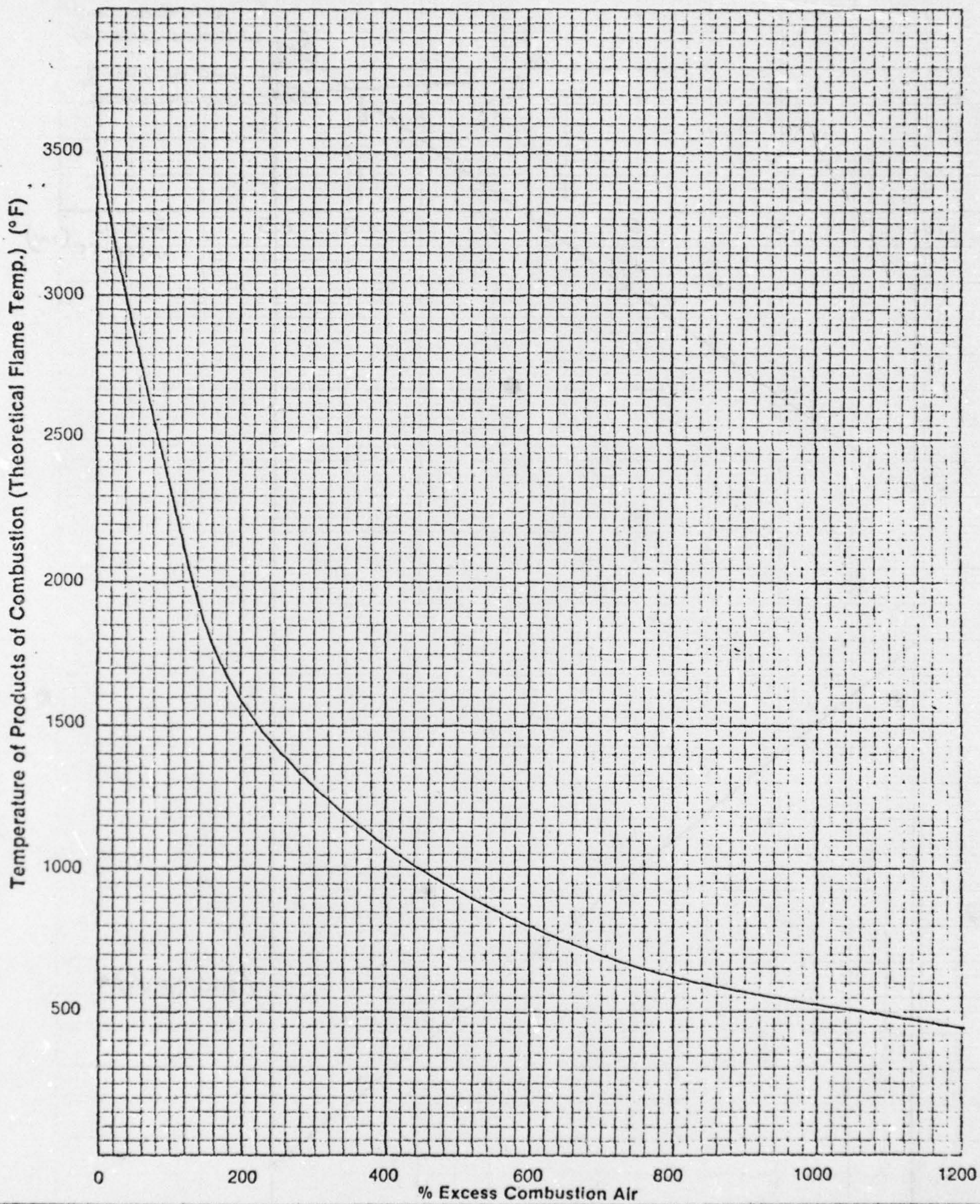


FIGURE 16

FIGURE 17

THEORETICAL FLAME TEMPERATURE FOR NATURAL GAS VS PERCENT EXCESS COMBUSTION AIR



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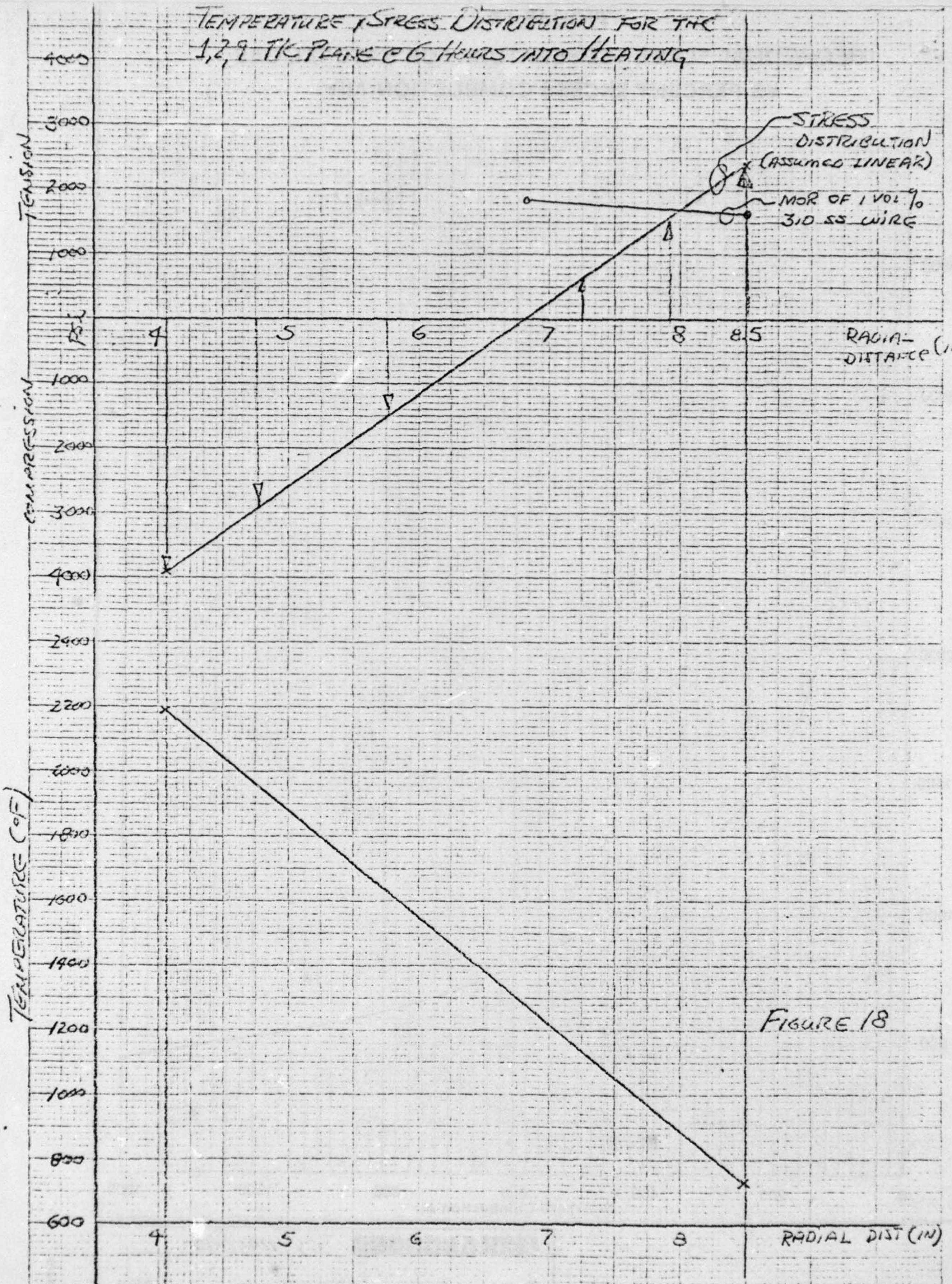
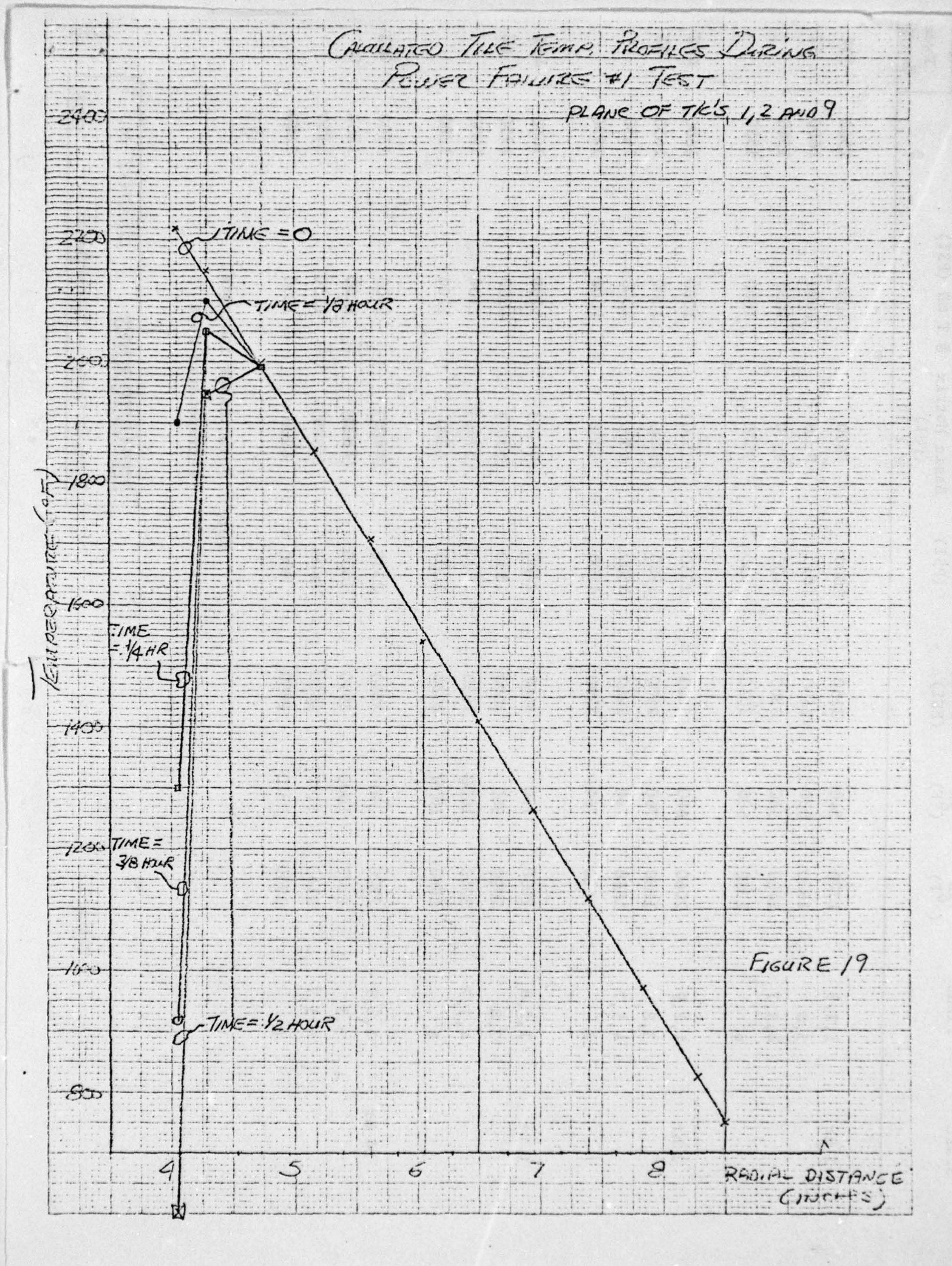


TEMPERATURE / STRESS DISTRIBUTION FOR THE
1,2,9 TK PLANE @ 6 HOURS INTO HEATING
TENSION
COMPRESSION
PSI
4000
3000
2000
1000
0
1000
2000
3000
4000
STRESS DISTRIBUTION (ASSUMED LINEAR)
MOR OF 1 VOL % 310 SS WIRE
4
5
6
7
8
8.5
RADIAL DISTANCE (IN)
TEMPERATURE (°F)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
4
5
6
7
8
RADIAL DIST (IN)

FIGURE 18



CALCULATED TILE TEMP. PROFILES DURING
POWER FAILURE #1 TEST
PLANE OF TK'S 1, 2 AND 9
2400
2200
2000
1800
1600
1400
1200
1000
800
TIME = 0
TIME = 1/8 HOUR
TIME = 1/4 HR
TIME = 3/8 HOUR
TIME = 1/2 HOUR
TEMPERATURE (°F)
4
5
6
7
8
RADIAL DISTANCE (INCHES)

FIGURE 19

Start	Plane	ID (^{o}F)	OD (^{o}F)	Stress (PSI)	Stress (PSI)	Strength of Basic Matrix (PSI) @ T ID	Basic Matrix @ T OD (PSI)	Reinforced Mat'l.e	Exces Tensic
1 hr	1,2,9	1770	540	3250	2000	7600	1000	1500	33%
	3,8	1630	630	2650	1650	8500	1000	1600	3%
	4,5,7	1420	560	2300	1400	9500	1000	1500	
	6	1310	590	2050	1050	9500	1000	1550	
3 hr	1,2,9	2060	640	3800	2350	(5500)	1000	1600	47%
	3,8	1850	760	2900	1800	7000	1000	1650	9%
	4,5,7	1660	760	2400	1500	8300	1000	1650	
	6	1530	760	2200	1100	9300	1000	1650	
6 hr	1,2,9	2190	730	3900	2400	(4600)	1000	1650	45%
	3,8	2090	960	3000	1850	(5300)	1000	1750	6%
	4,5,7	2040	1050	2650	1600	(5700)	1100	1800	
	6	1880	1050	2350	1200	6200	1100	1800	
14 hr	1,2,9	2220	790	3800	2350	(4400)	1000	1700	38%
	3,8	2170	1060	2950	1800	(4800)	1100	1800	0
	4,5,7	2160	1170	2650	1600	(4900)	1150	1850	
	6	1960	1310	1850	950	6200	1200	1800	

Note: Parentheses indicate extrapolated data

TABLE 1

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